Crystalline mirrors for GW detectors

M. Leonardi on behalf of the KAGRA collaboration

Summary

1. Introduction to KAGRA
   - Performances during O3GK
   - Current status of upgrades
2. KAGRA's experience with crystalline mirrors (substrates)
   - Problem encountered
   - Substrate characterization
   - Lessons for 3G detectors

Part 1: introduction to KAGRA

The Japanese GW detector: KAGRA

KAGRA is located near Kamioka in Gifu prefecture, one hour drive from Toyama.

Unique features:

1. Underground site
2. Cryogenic operation

The Japanese GW detector: KAGRA

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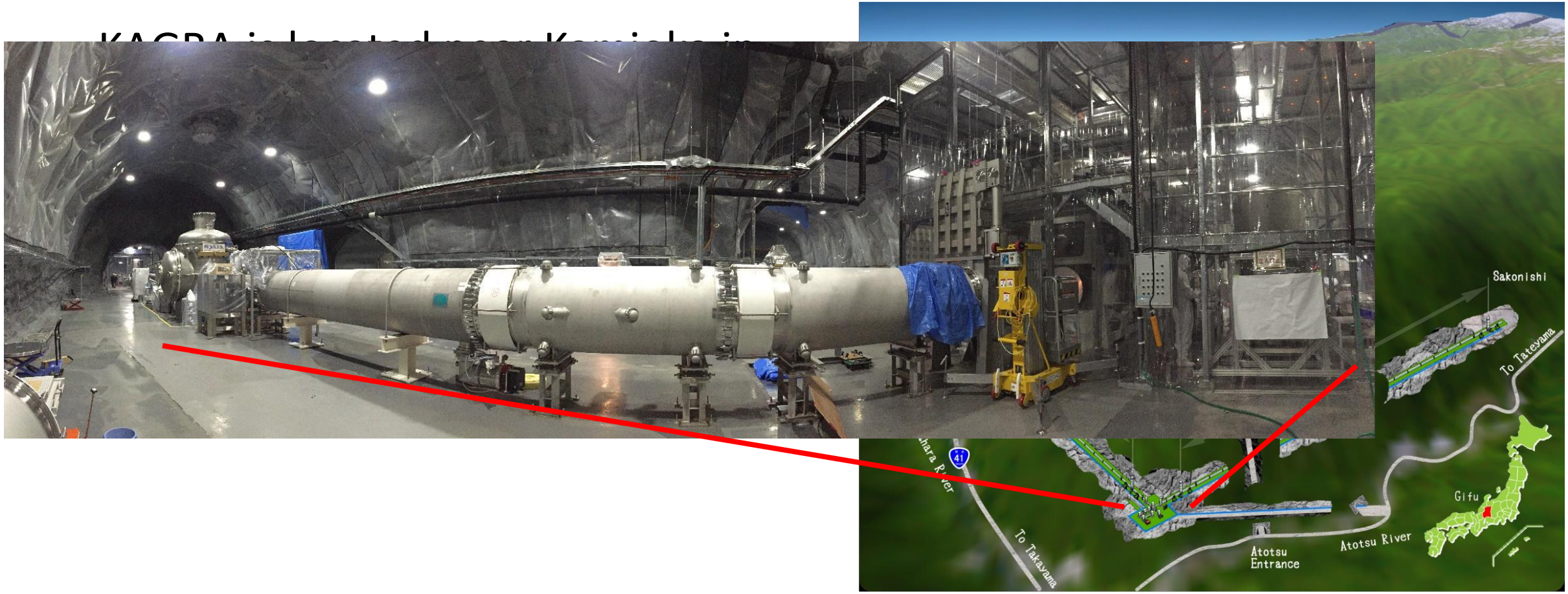
The Japanese GW detector: KAGRA



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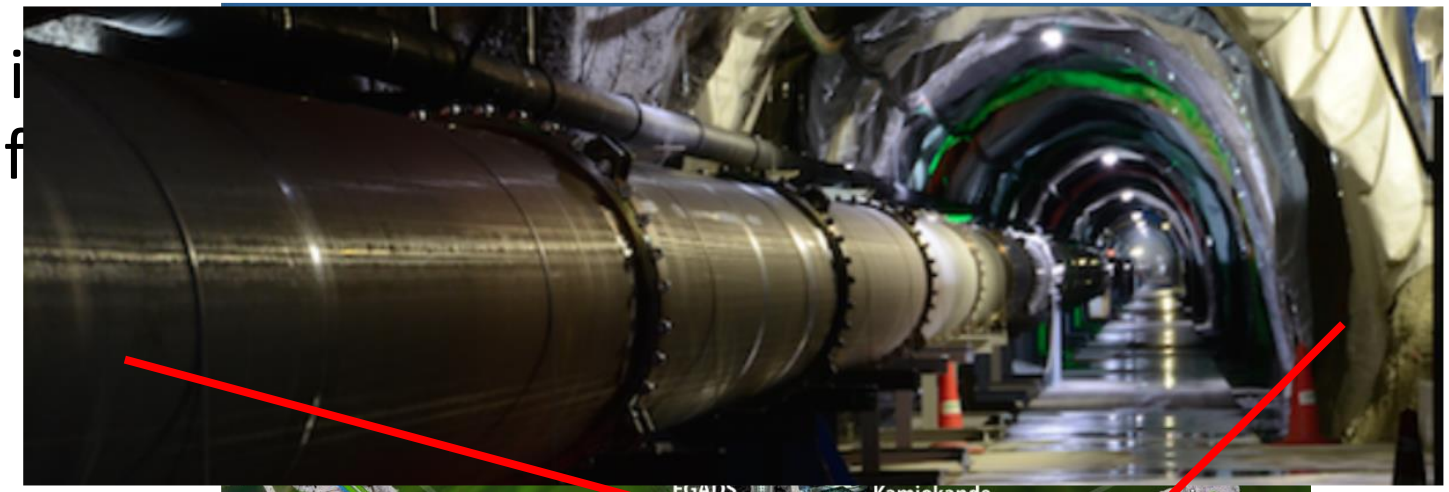
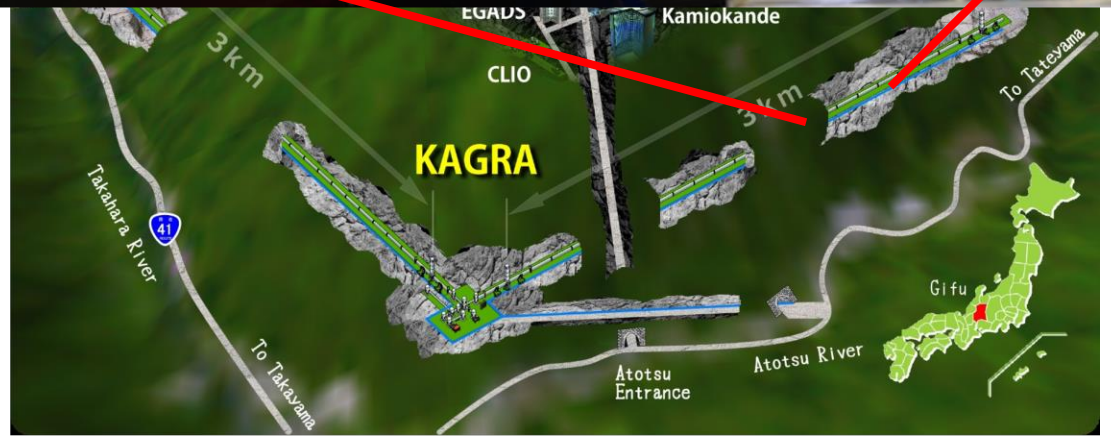


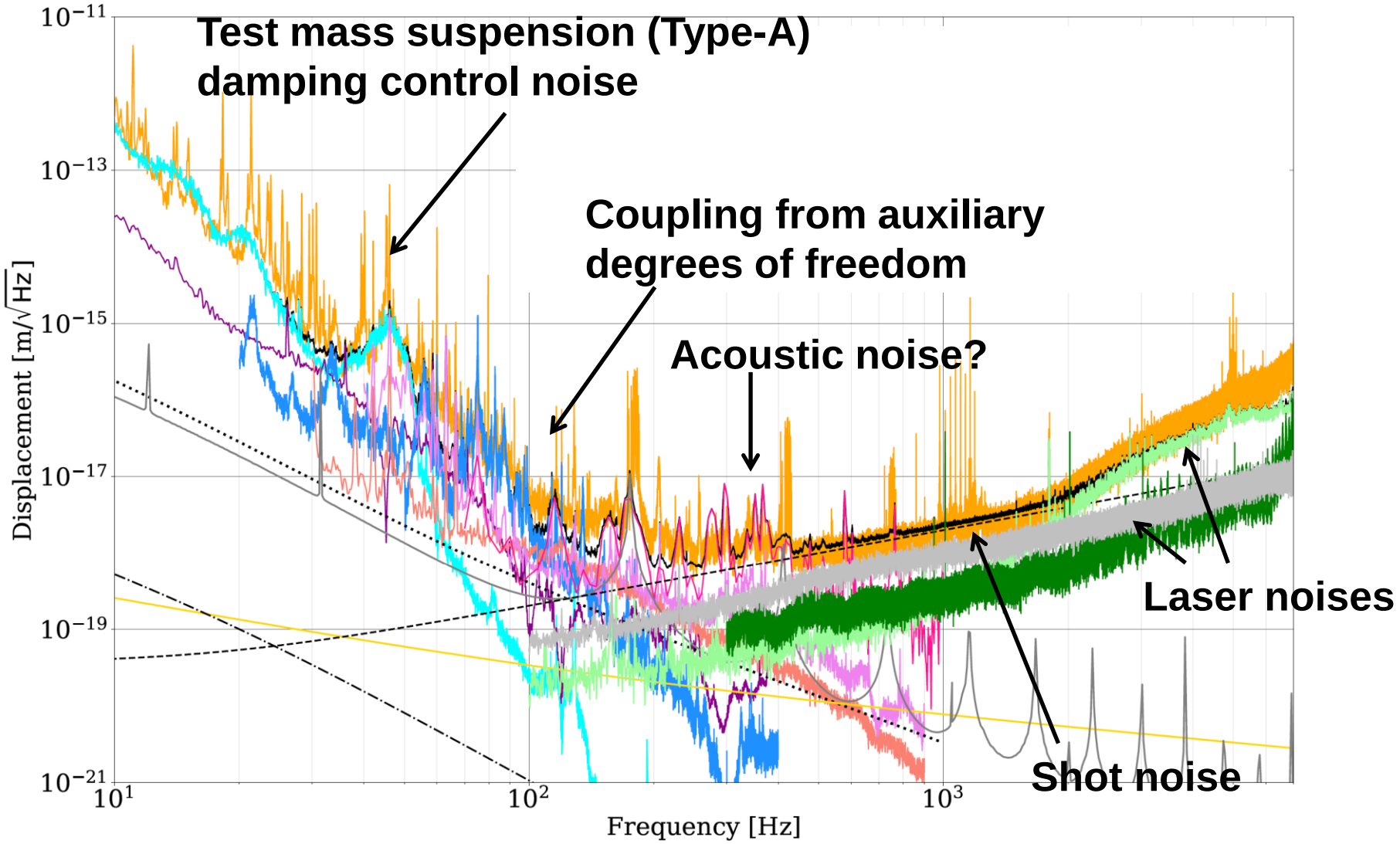


Last news from KAGRA

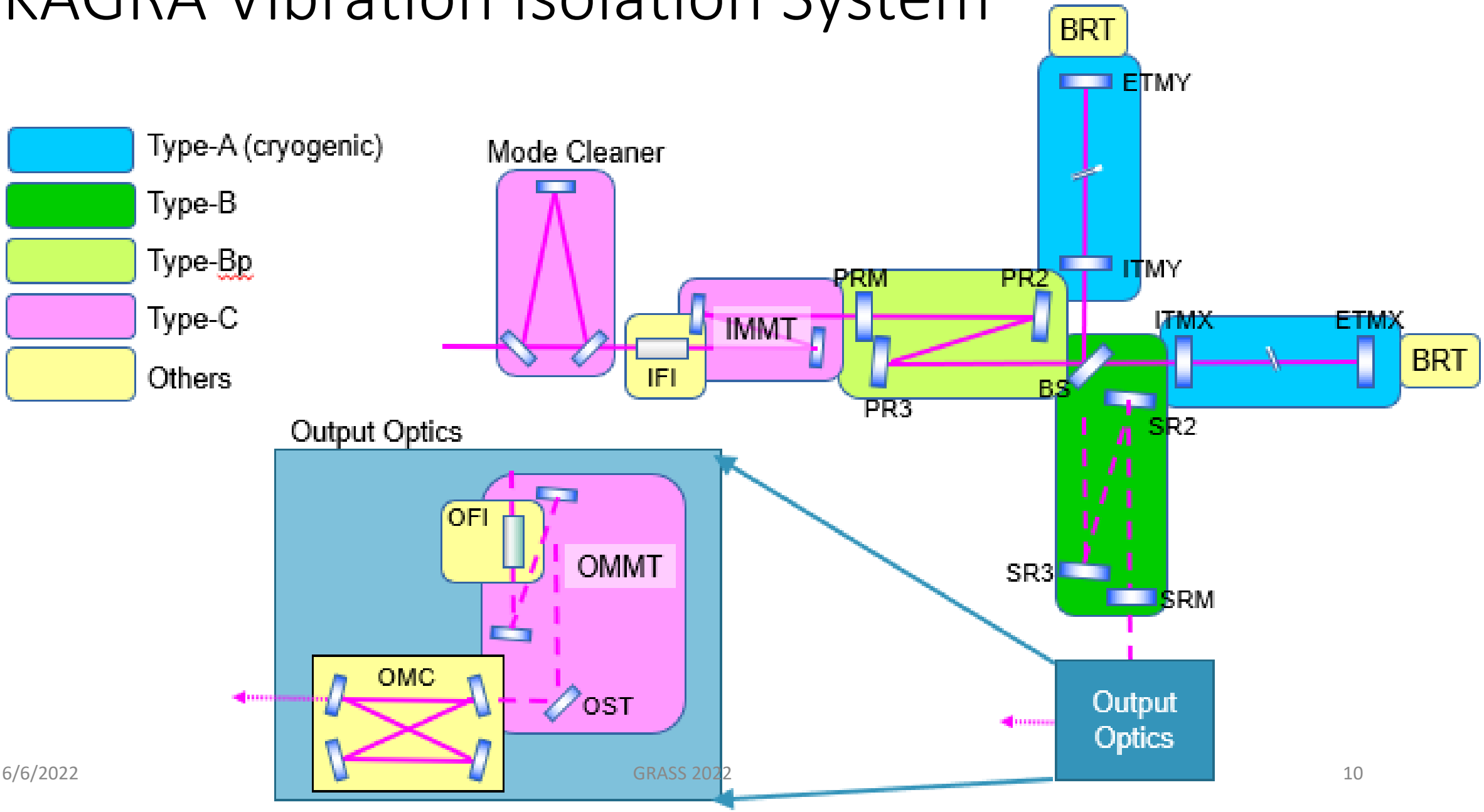
- May 2020: O3GK finished (~1Mpc BNS range)
- July – Oct. 2020: RSE trial
- Oct. 2020 -
  - Opened Vacuum Chambers
  - Upgrade of vibration isolation systems
  - IMC commissioning
  - IFO re-alignment
  - X-arm single arm commissioning
  - ALS commissioning
  - Pcal upgrade
  - PEM upgrade

O3GK noise budget

arXiv:2203.07011

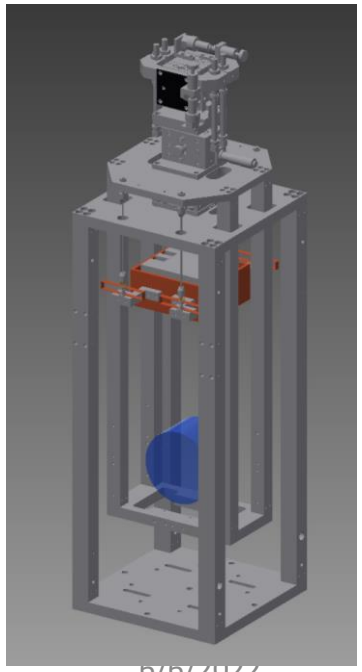


KAGRA Vibration Isolation System

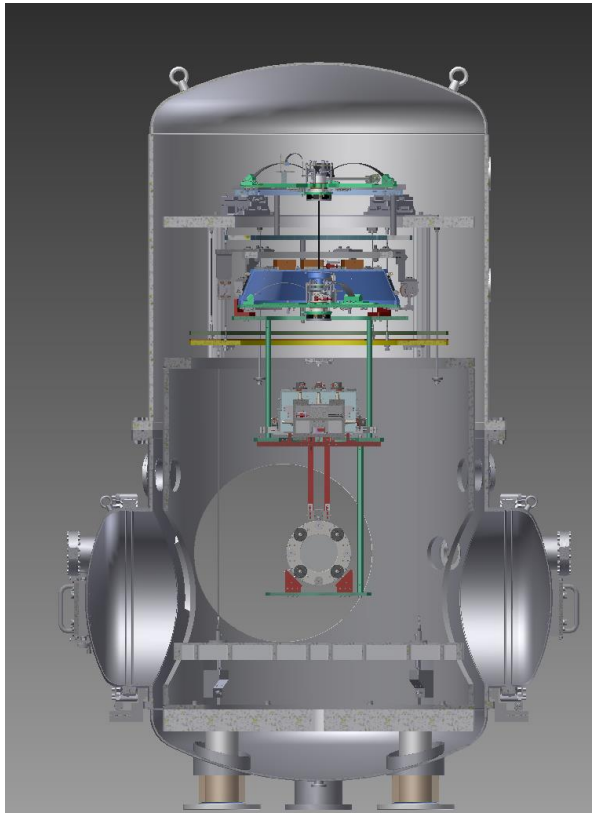


KAGRA Suspension Types

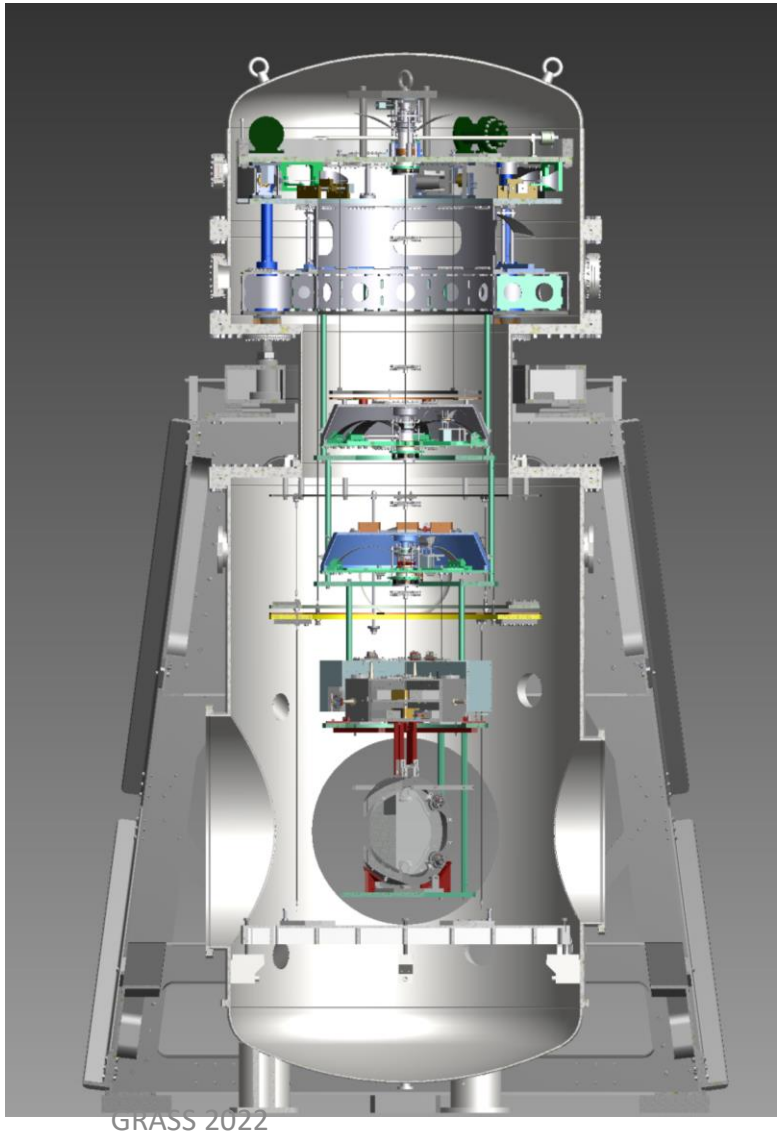
Type-C



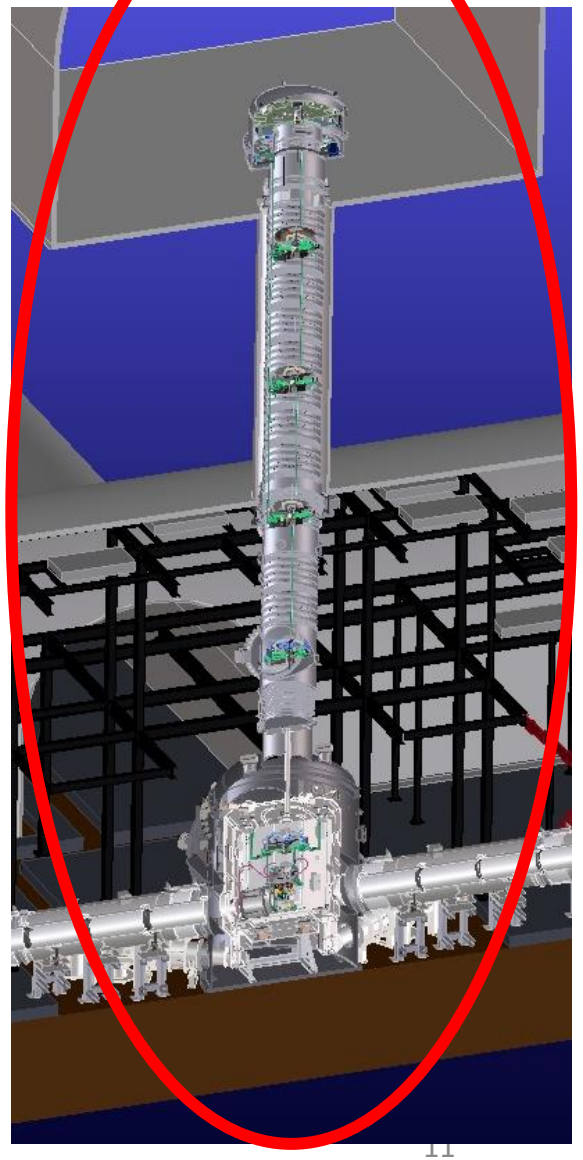
Type-Bp



Type-B

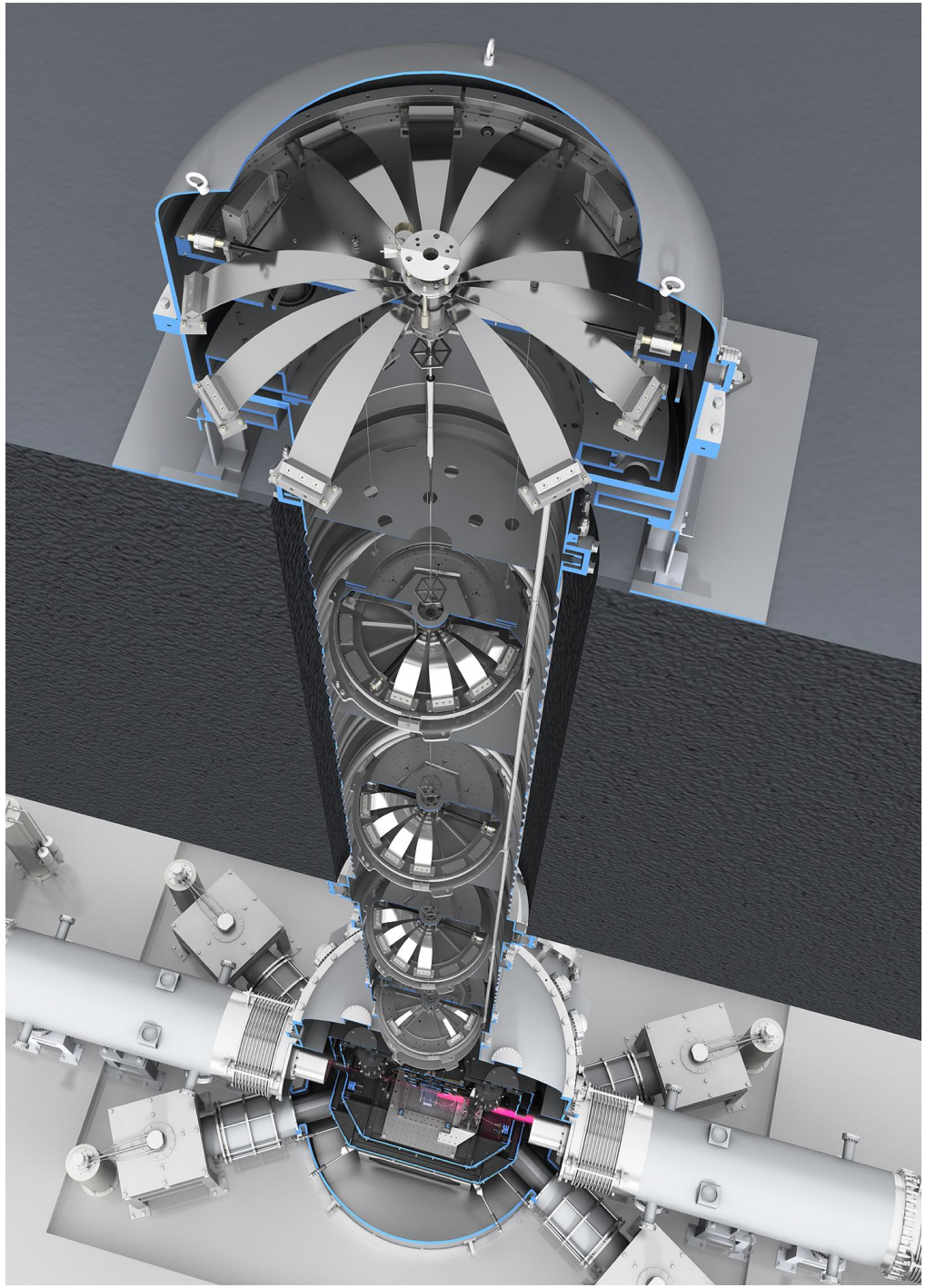


Type-A

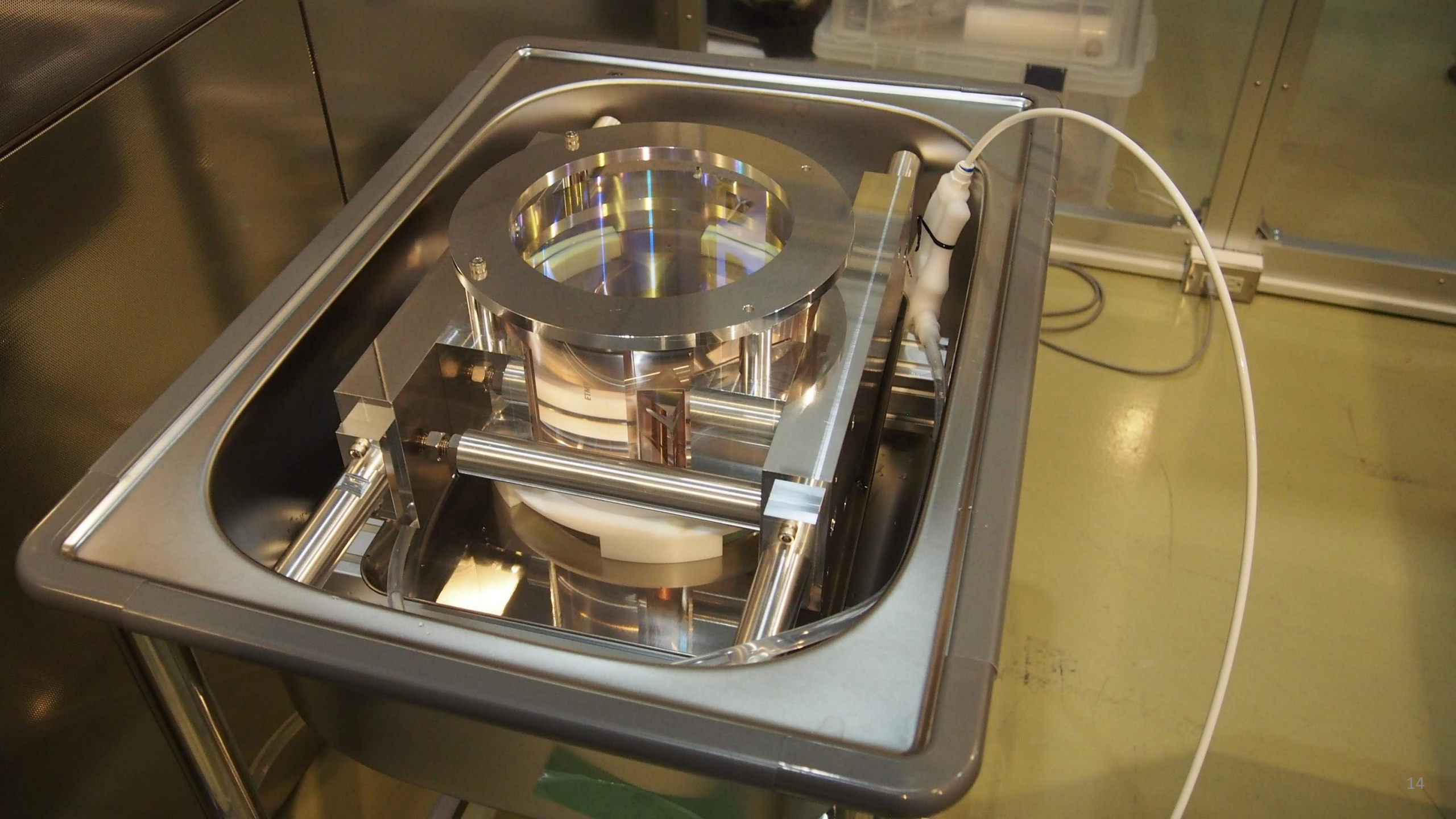


Fixed a number of issues with the room temperature part

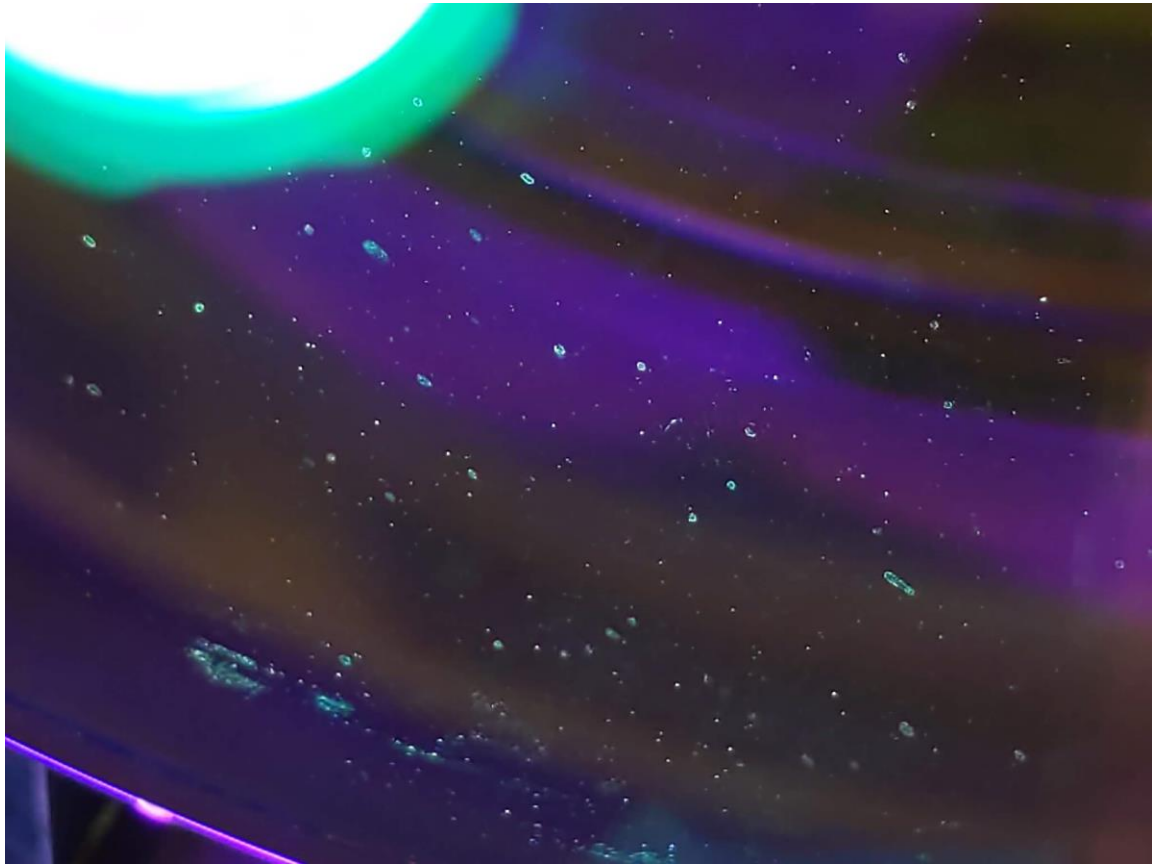
- Some of the filters were stuck in O3GK
  - Now fixed
- ITM top GAS filter blades were replaced
- New accelerometers for the top stages
- LVDT driver coupling reduced
- Many other messy problems (cables touching, vacuum leaks, …)



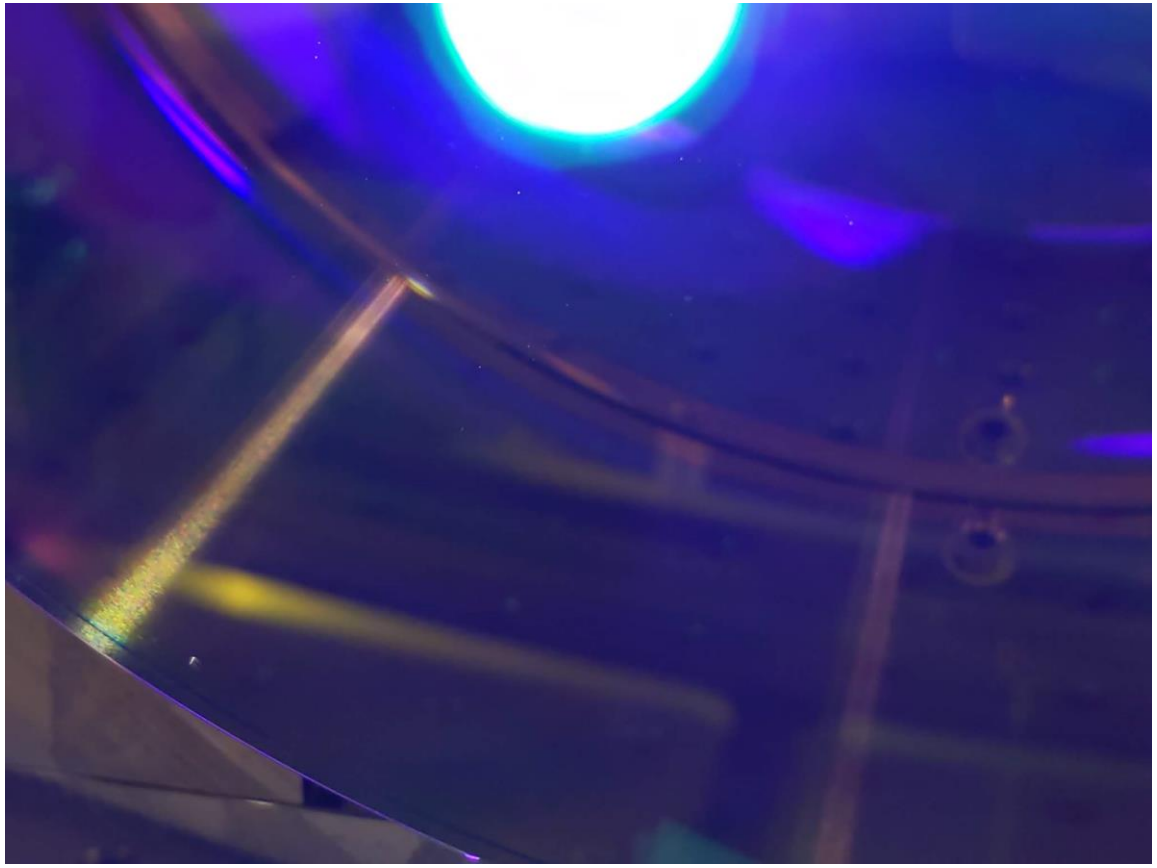
Contamination of the ETMY cryostat and mirror



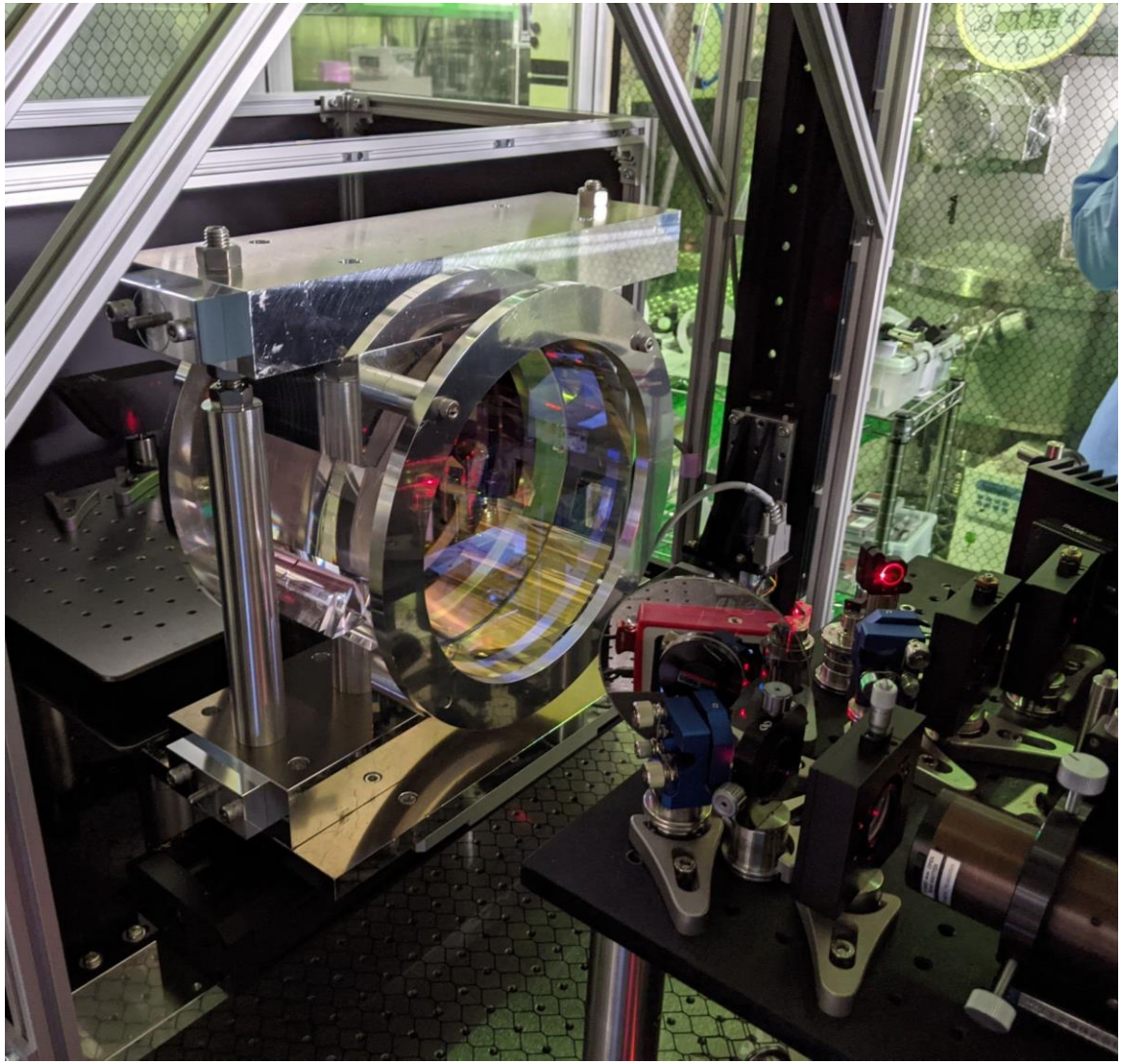
Before

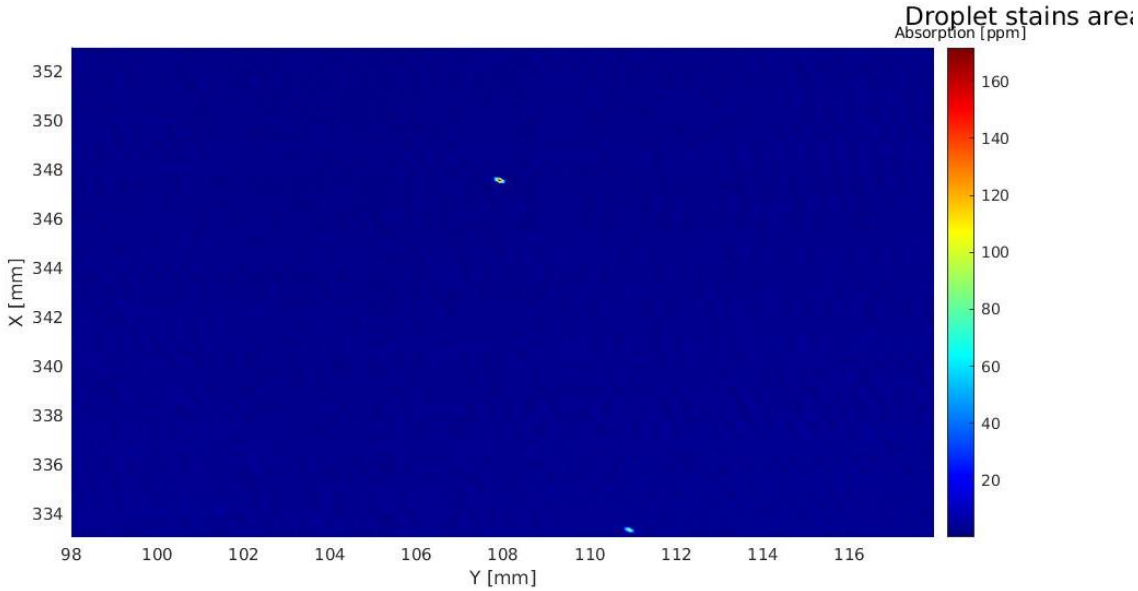


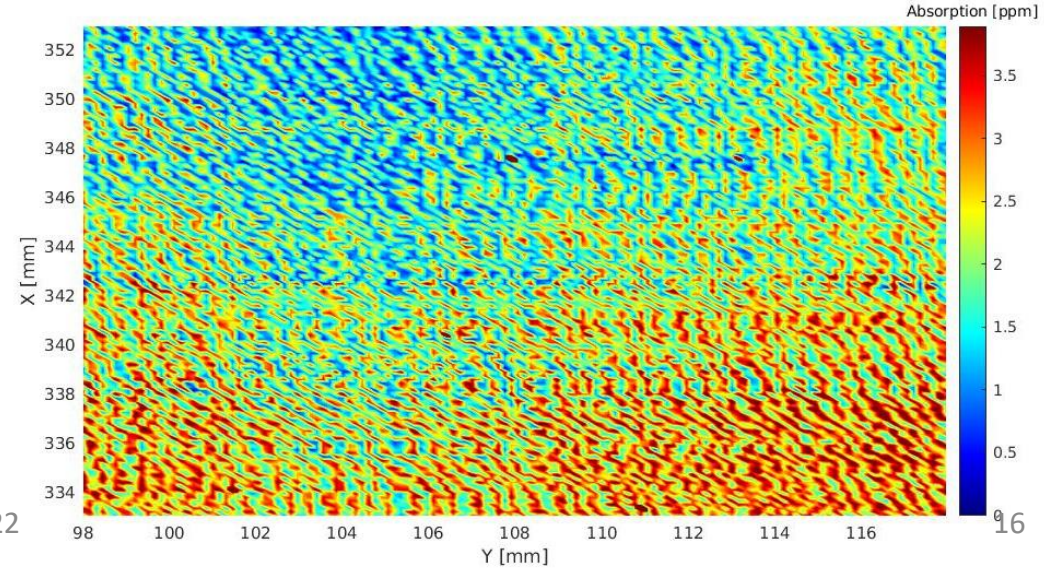
After



Surface Absorption Measurement of the Cleaned Mirror

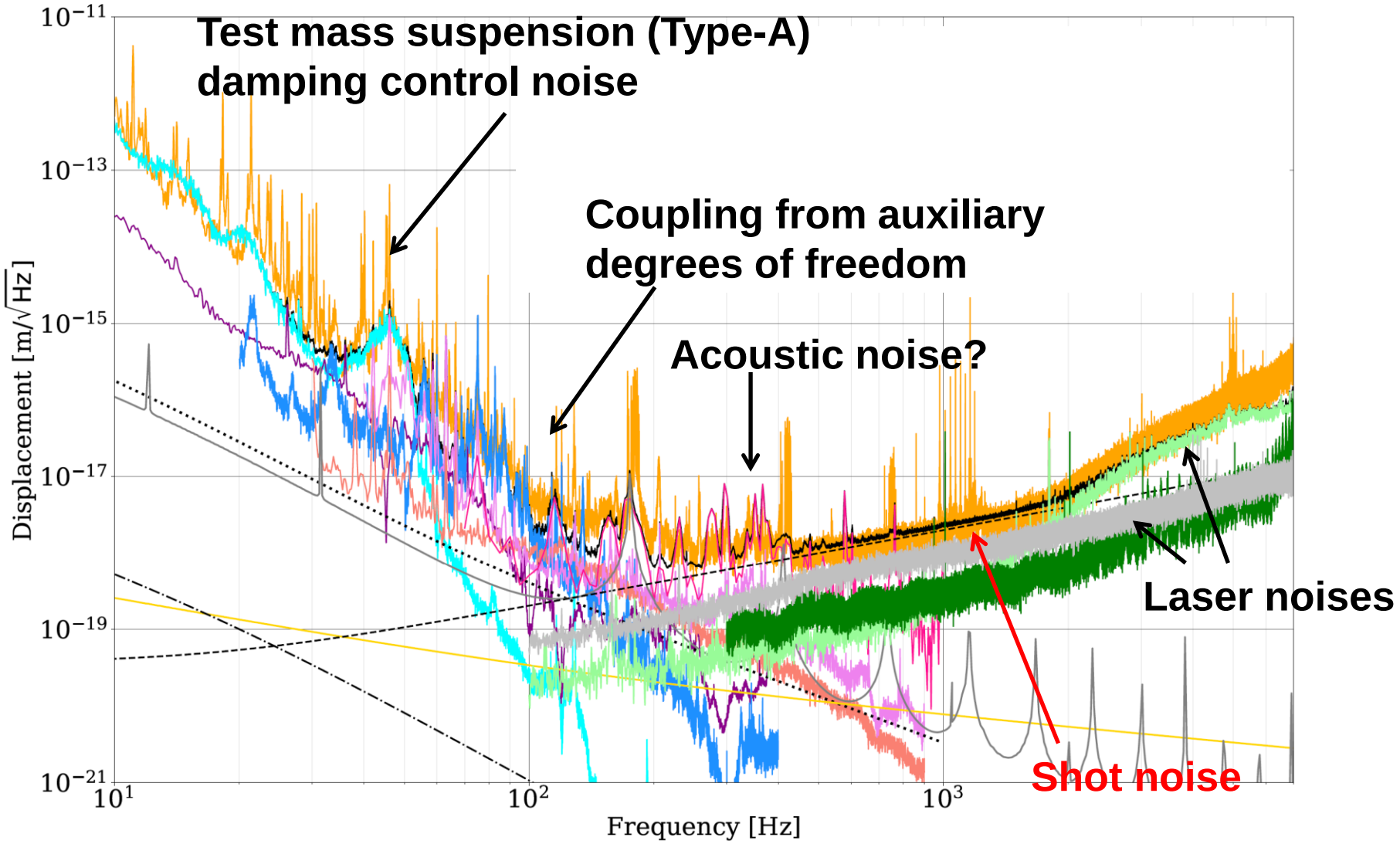




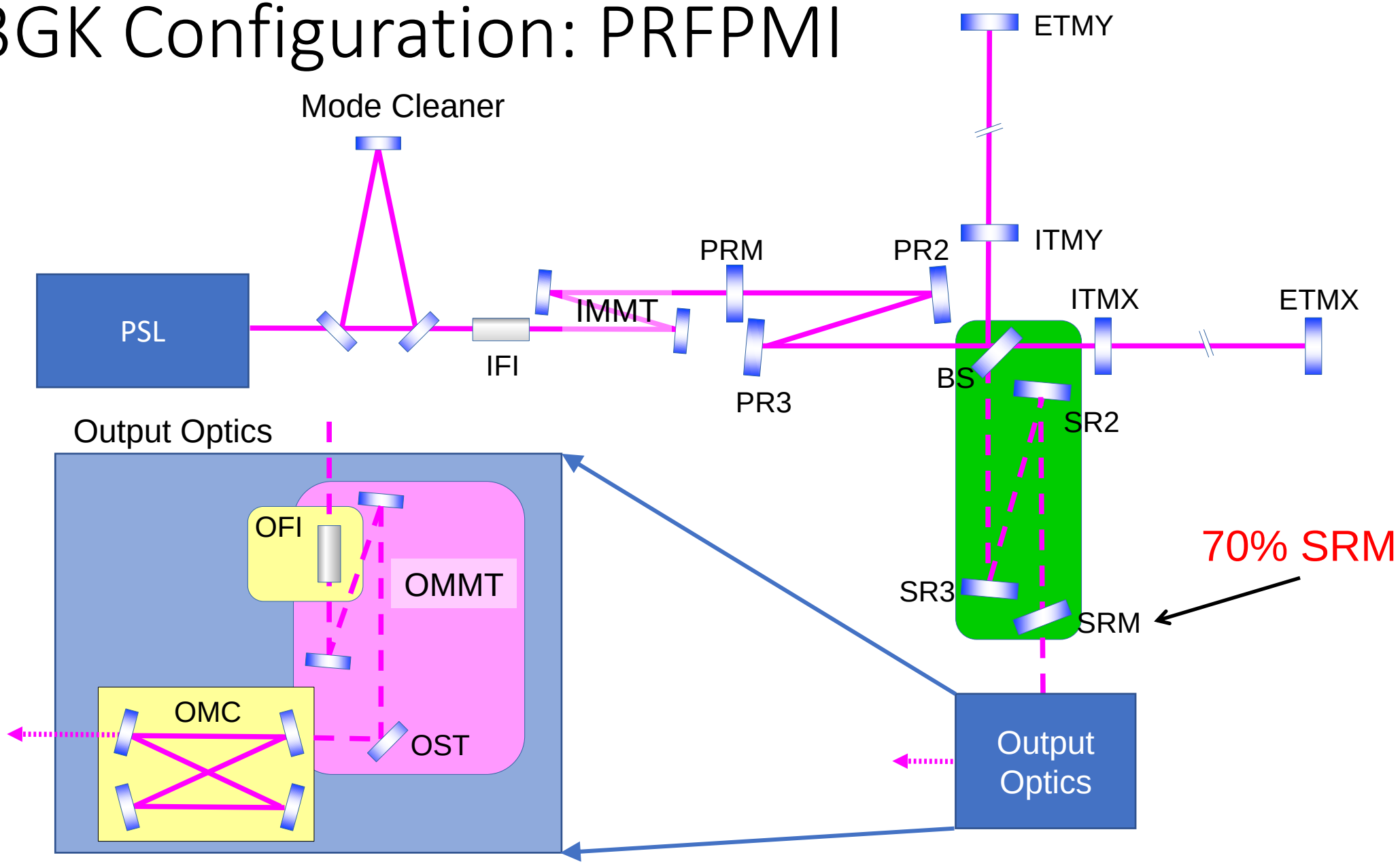


O3GK noise budget

arXiv:2203.07011



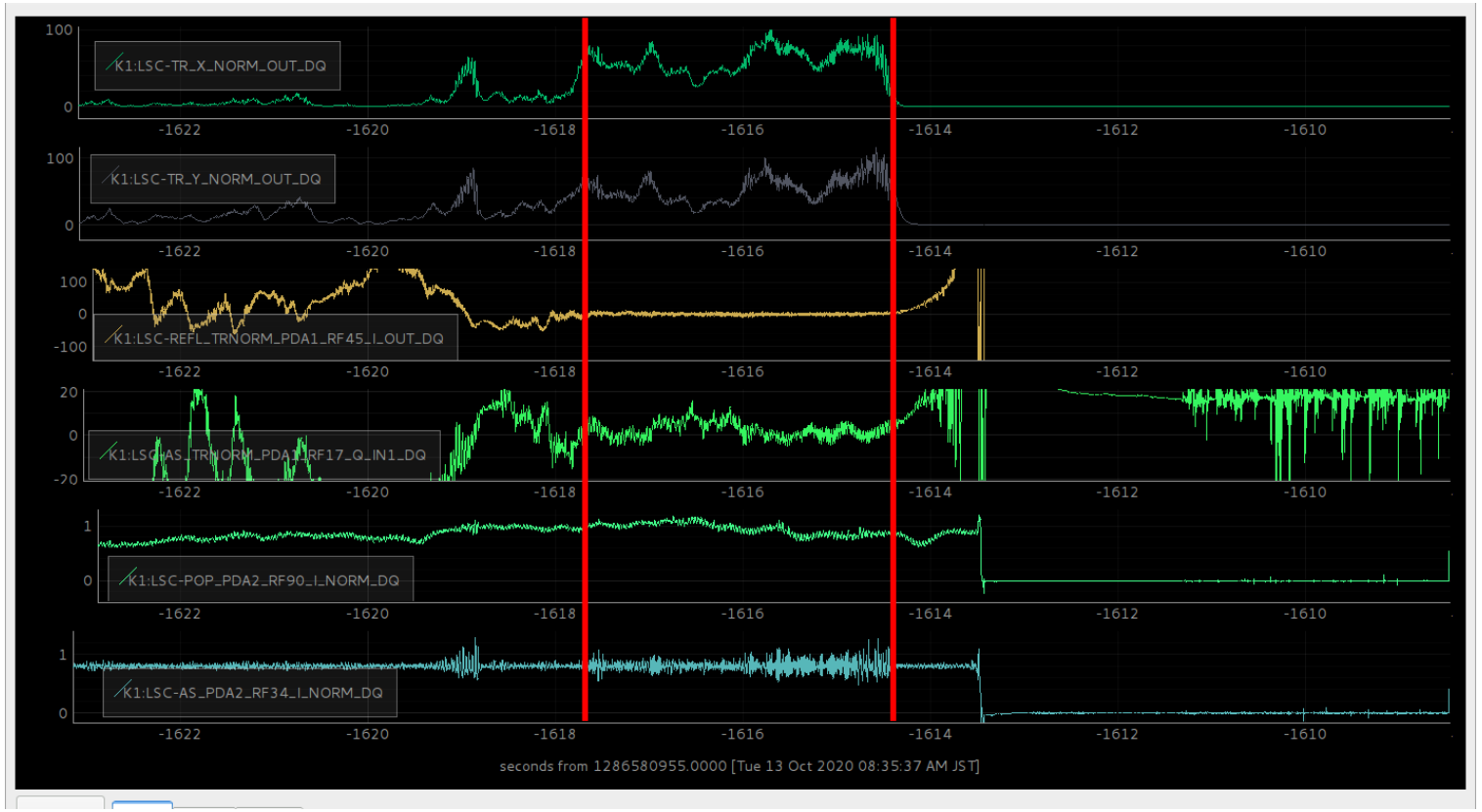
O3GK Configuration: PRFPMI



RSE lock trial

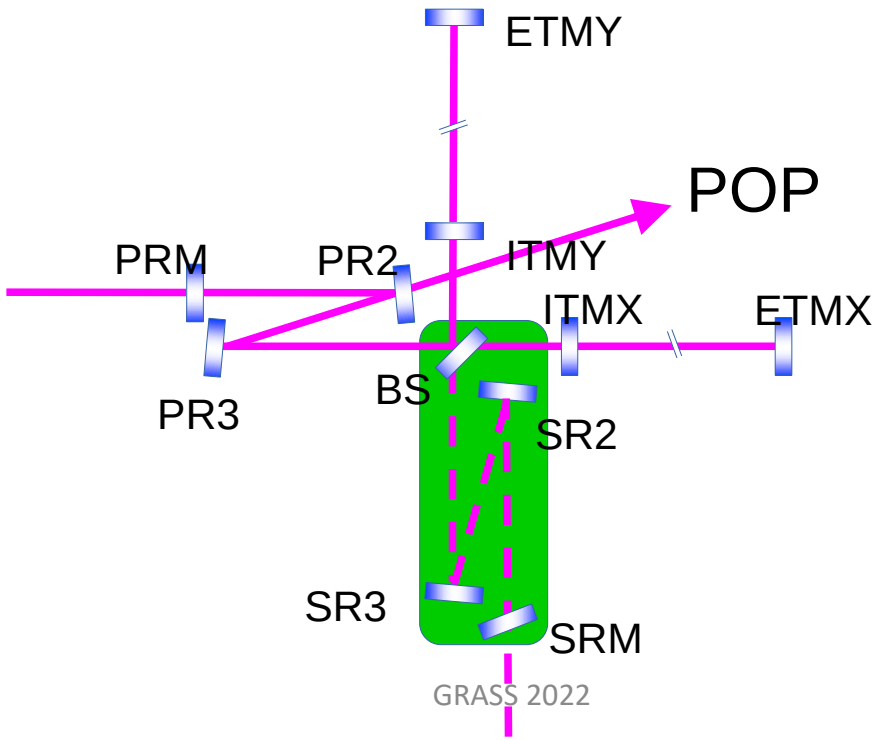
- Suspensions were not quiet enough
- Not enough time to tune feedback filters
- No WFS implemented

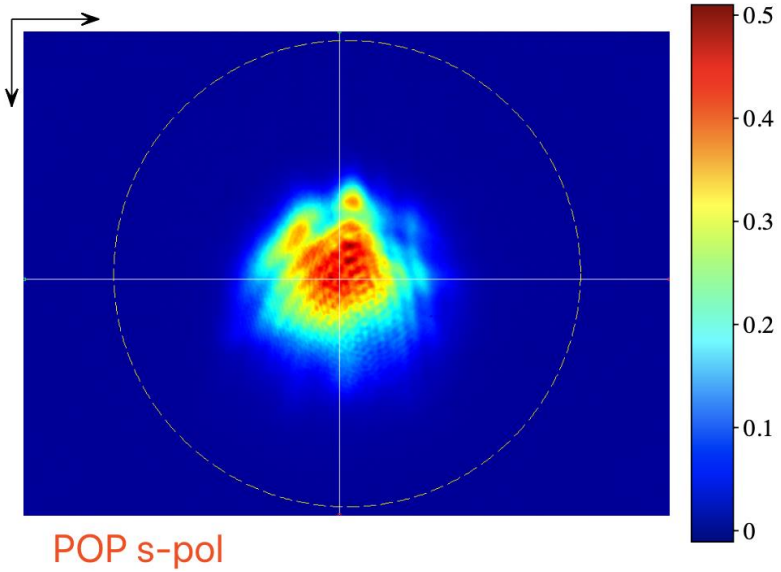
RSE lock ~ 2 sec

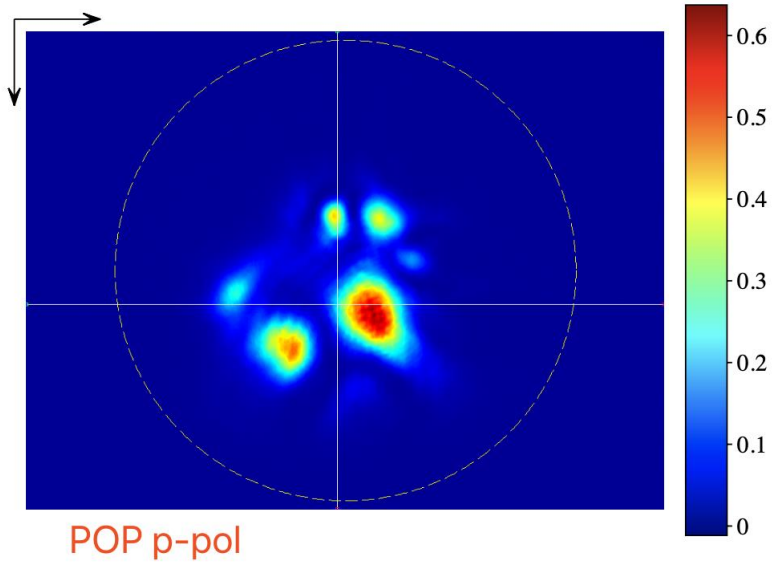


Alignment Sensing and Control

- ASC is much more difficult and messier than LSC (Universal Truth)
- It is especially hard for KAGRA because of the birefringence







Part 2: KAGRA experience with crystalline mirrors

Recap on sapphire

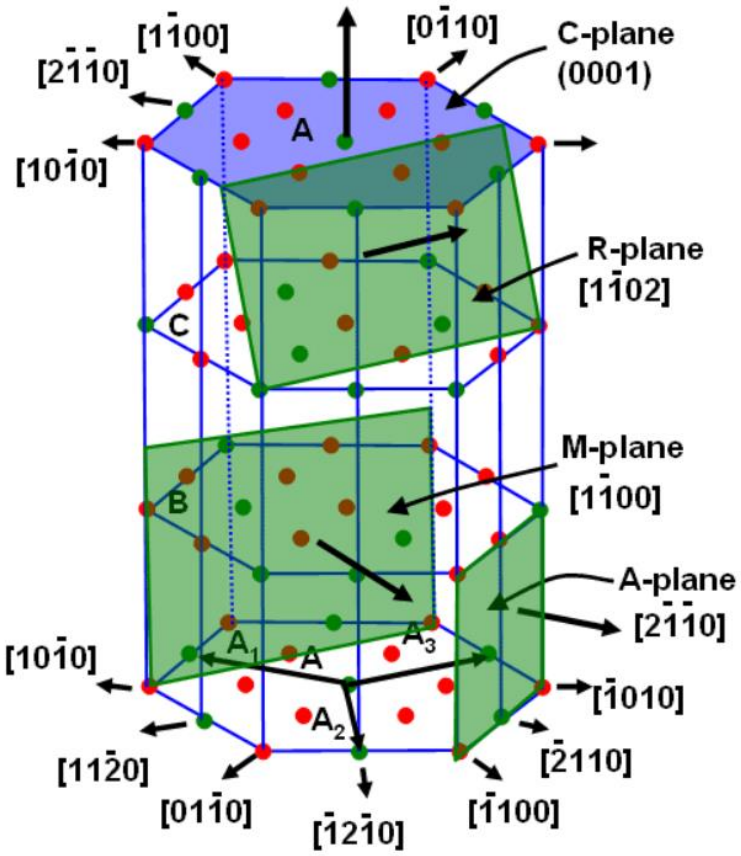
Sapphire substrate:

- Absorption:

  well known problem from design phases

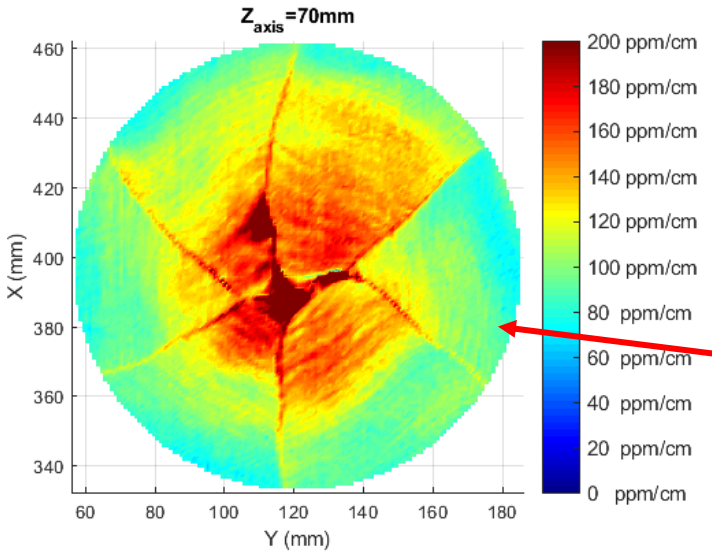
- Birefringence:

  partially unexpected problem

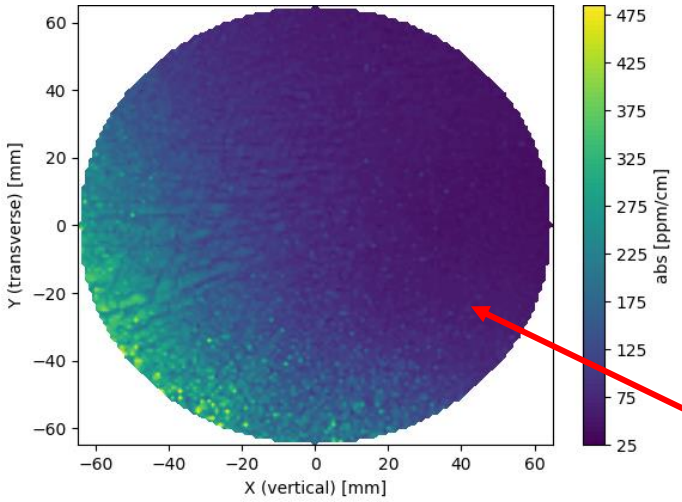


Growth orientation impact on opt. absorption spatial distribution

C-axis growth:



A-axis growth:



Company B	S1	S2	S3
#0	167.6 (35.5)	126.8 (41.7)	26.6 (17.0)
#1	96.1 (31.2)	93.1 (28.7)	99.3 (38.0)
#2	27.1 (11.0)	31.5 (10.5)	24.8 (10.5)
#3	73.3 (23.2)	137.6 (34.7)	143.1 (39.9)
#4	130.9 (39.1)	99.4 (22.7)	139.5 (35.7)
#5	85.3 (34.7)	56.5 (14.9)	119.6 (39.9)
#6	184.9 (54.5)	140.9 (36.1)	201.6 (54.8)
#7	65.1 (14.9)	62.2 (16.6)	91.2 (28.7)
#8	111.4 (34.1)	66.3 (18.6)	143.2 (30.3)
#10	112.5 (51.7)	38.7 (17.6)	32.9 (13.7)
#11	21.2 (12.3)	22.8 (18.2)	33.4 (23.4)
#12	77.1 (24.2)	83.6 (30.2)	89.7 (31.1)

Company A	S1	S2	S3
#1(F62-22)	41.1 (23.1)	64.3 (23.3)	59.9 (19.8)
#2 (F47-21)	72.1 (31.1)	87.3 (38.2)	93.4 (36.5)
#3 (AC-179)	60.6 (76.0)	37.7 (17.3)	47.7 (34.1)
#4 (F39-56)	94.0 (139.6)	305.3 (250.0)	160.2 (171.4)
#5 (MMK-1)	106.98 (45.68)	69.02 (22.91)	76.0 (31.0)
#6 (MMK-2)	216.47 (108.01)	82.82 (30.90)	99.4 (49.5)
#7 (C14-11c)	114.2 (95.5)	79.3 (49.9)	72.4 (42.7)
#8 (OC-1)	86.6 (45.7)	69.5 (35.5)	58.0 (25.2)

Dislocation and optical absorption

Structural defects as preferential sites for the inclusion of absorbing centers

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scientific reports

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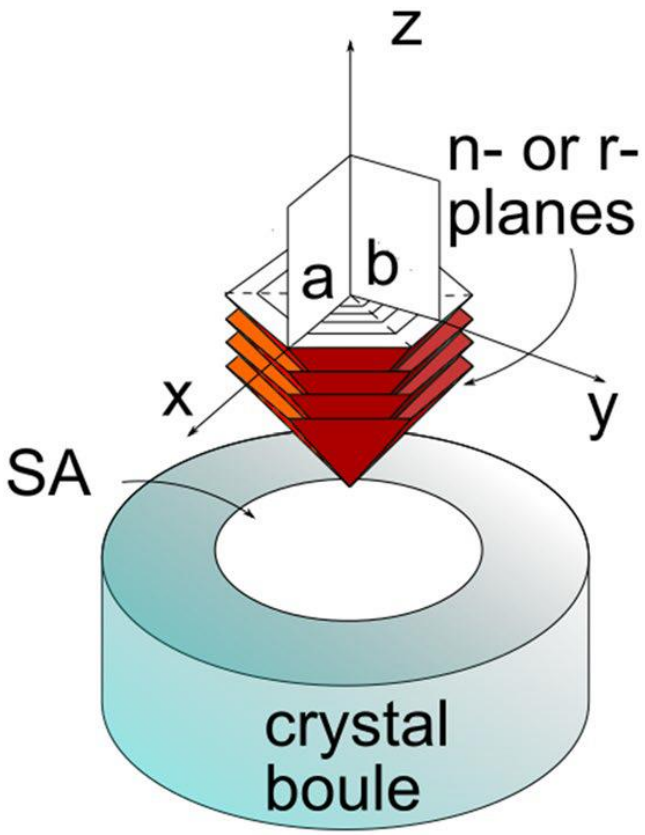
OPEN

3D characterization of low optical absorption structures in large crystalline sapphire substrates for gravitational wave detectors

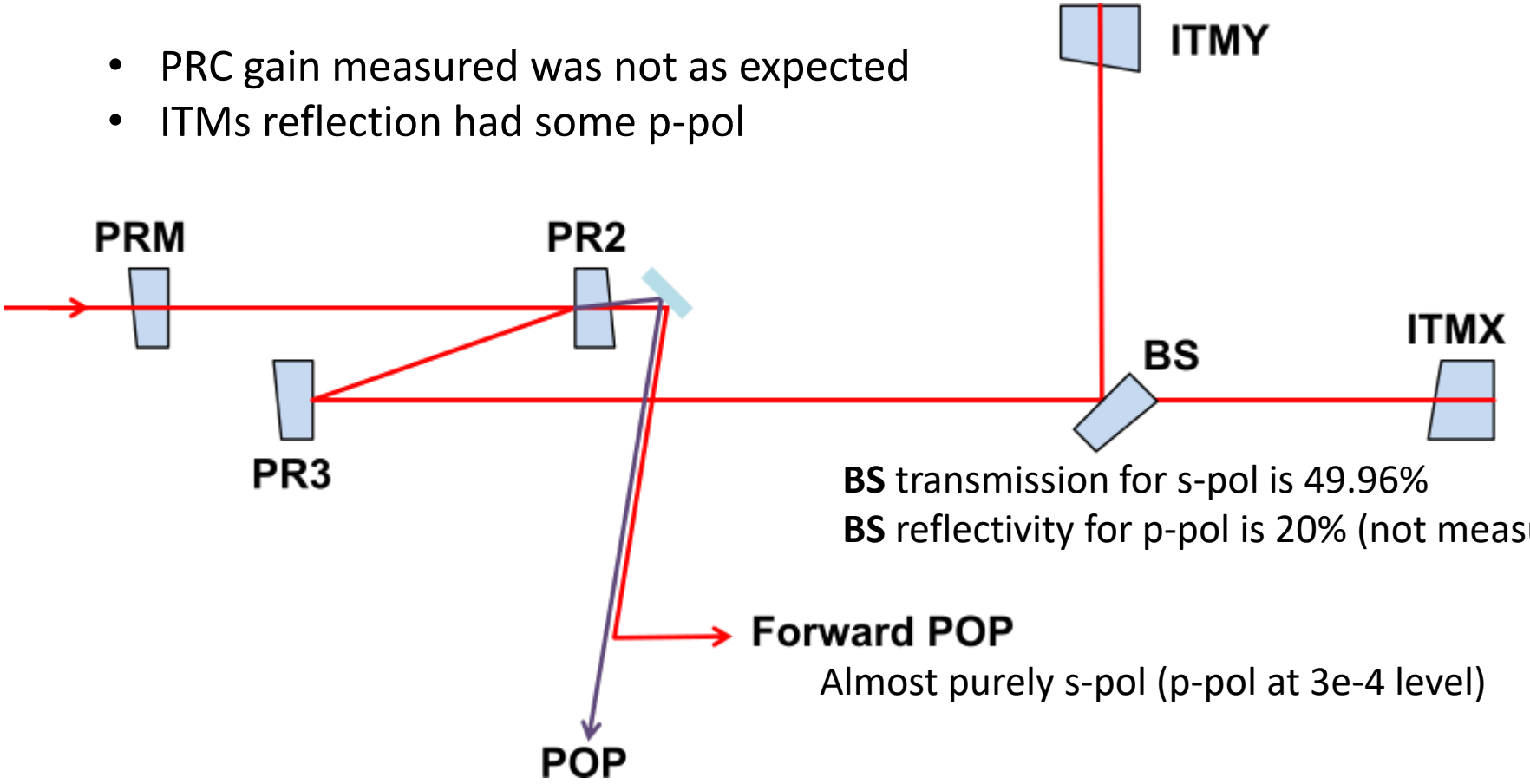
Manuel Marchiò[1,2], Matteo Leonardi[2], Marco Bazzan[3] & Raffaele Flaminio[2,4]

https://doi.org/10.1038/s41598-020-80313-1



Discovery of birefringence in KAGRA

- PRC gain measured was not as expected
- ITMs reflection had some p-pol



BS transmission for s-pol is 49.96%
BS reflectivity for p-pol is 20% (not measured)

Forward POP
Almost purely s-pol (p-pol at 3e-4 level)

6.1 % p-pol from ITMX single bounce
10.8 % p-pol from ITMY single bounce

A portion of input light in s-pol is converted to p-pol.

P-pol image observed in 2019

Constructing birefringence from TWE

$$\theta = -\frac{1}{2}\tan^{-1}\frac{TWE(45) - TWE(135)}{TWE(0) - TWE(90)}$$

$$\alpha_{-} = \frac{2\pi}{\lambda} \cdot \frac{TWE(0) - TWE(90)}{\cos 2\theta}$$

θ (angle between input polarization direction and e-axis) looks very random due to the inhomogeneity of sapphire substrate.

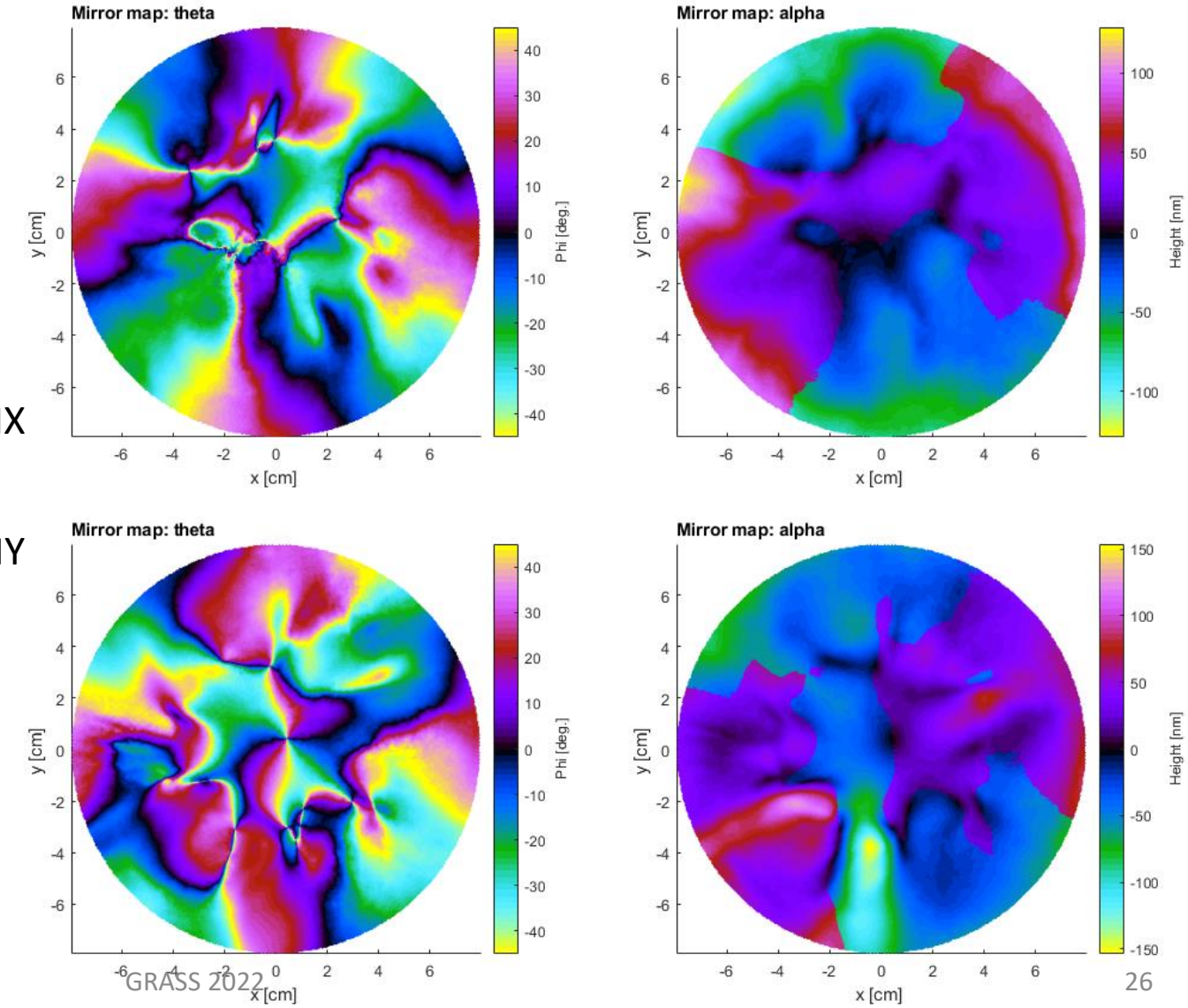
The PV value of α_{-} (one-way differential phase) is around ±150nm.

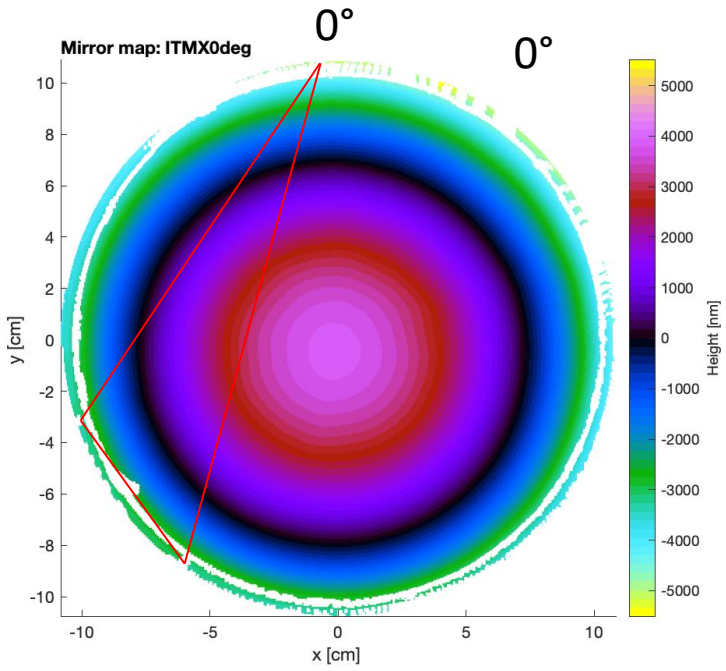
There are many sharp features, which is bad.

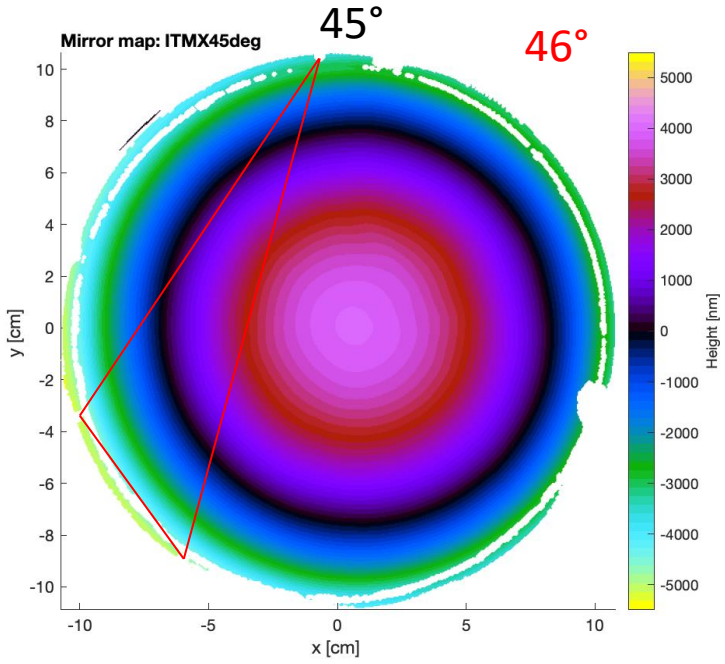
θ α_{-}

ITMX

ITMY

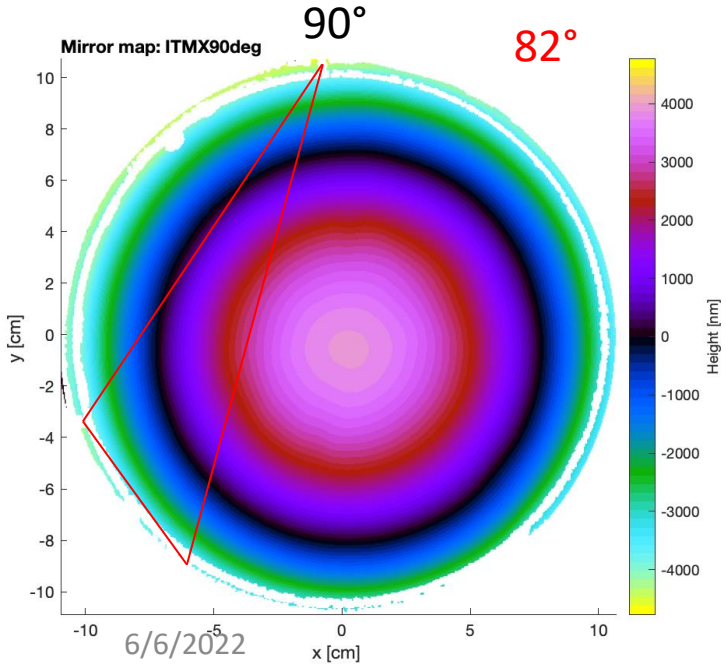


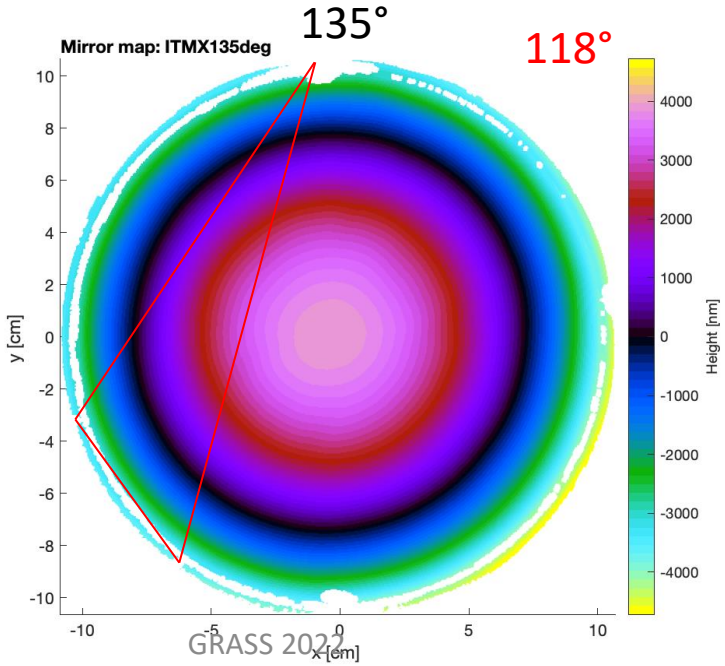




TWE maps

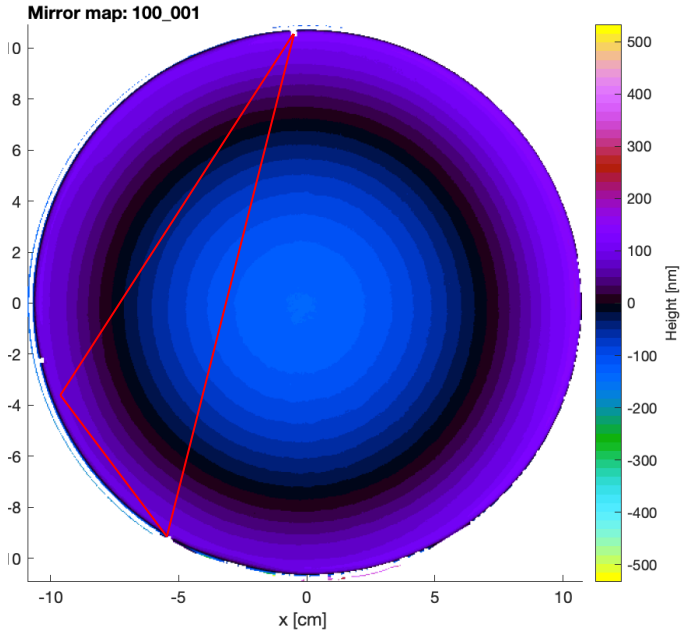
HRthAR





We calibrated rotation errors according to the markers in the TWE measurements.

HR maps



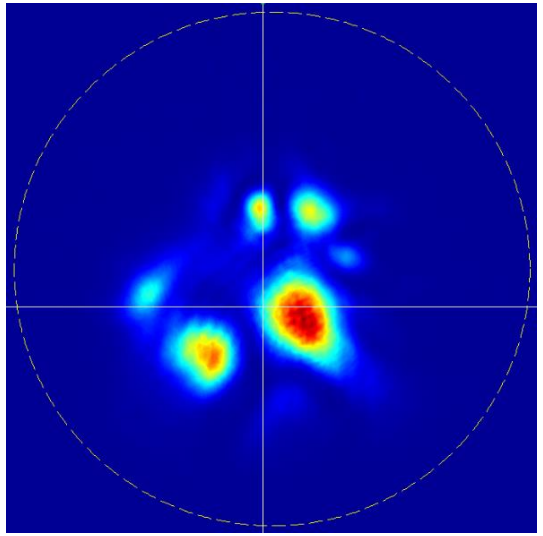
Rotation angles and markers in HR map masurements are different from TWE (HRthAR) measurements.

ITMX single bounce

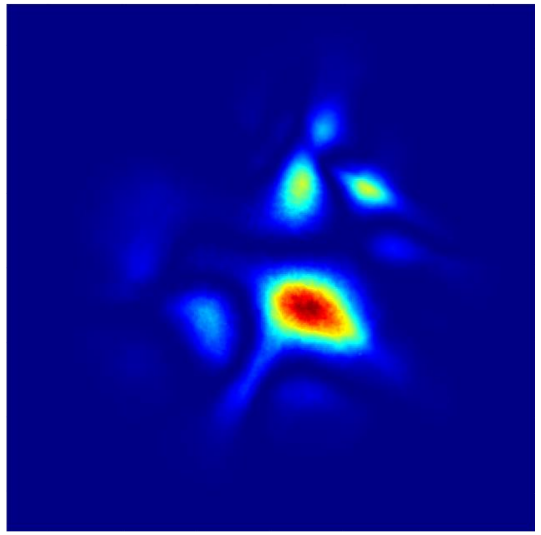
After careful calibrations for the TWE maps

P-pol shape

Measurement



Simulation

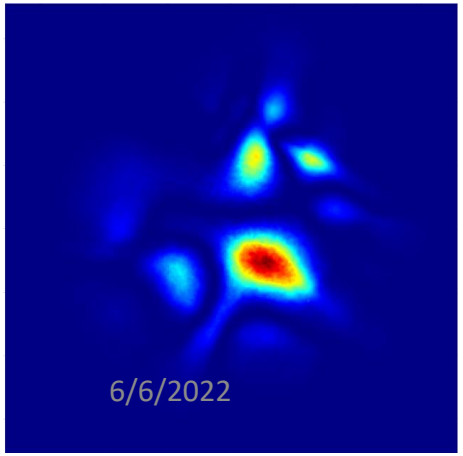


TEM00: <10%
1st mode: ~20%
2nd mode: ~10%
Higher order: >60%

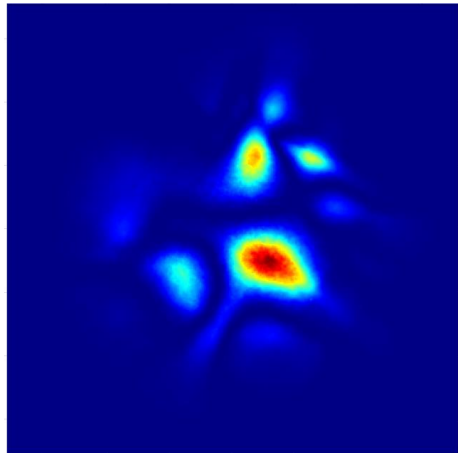
Calibration from rotation error of the 0° TWE map

One last thing, the 0° TWE map may be not measured at 0°.
If there are rotation errors (HR maps indicate the error is around 3°):

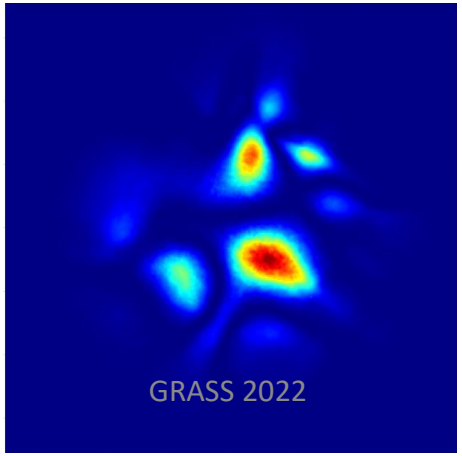
1°



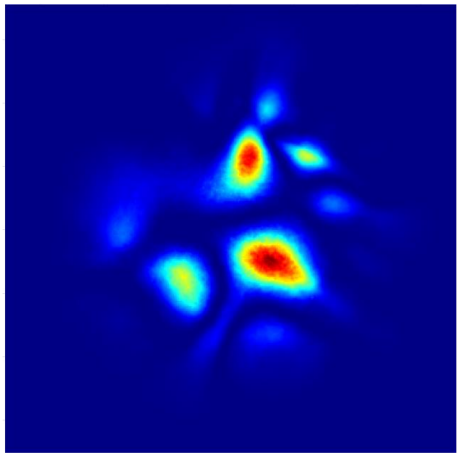
2°



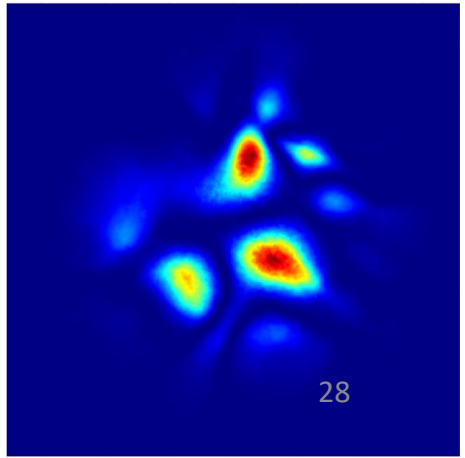
3°



4°

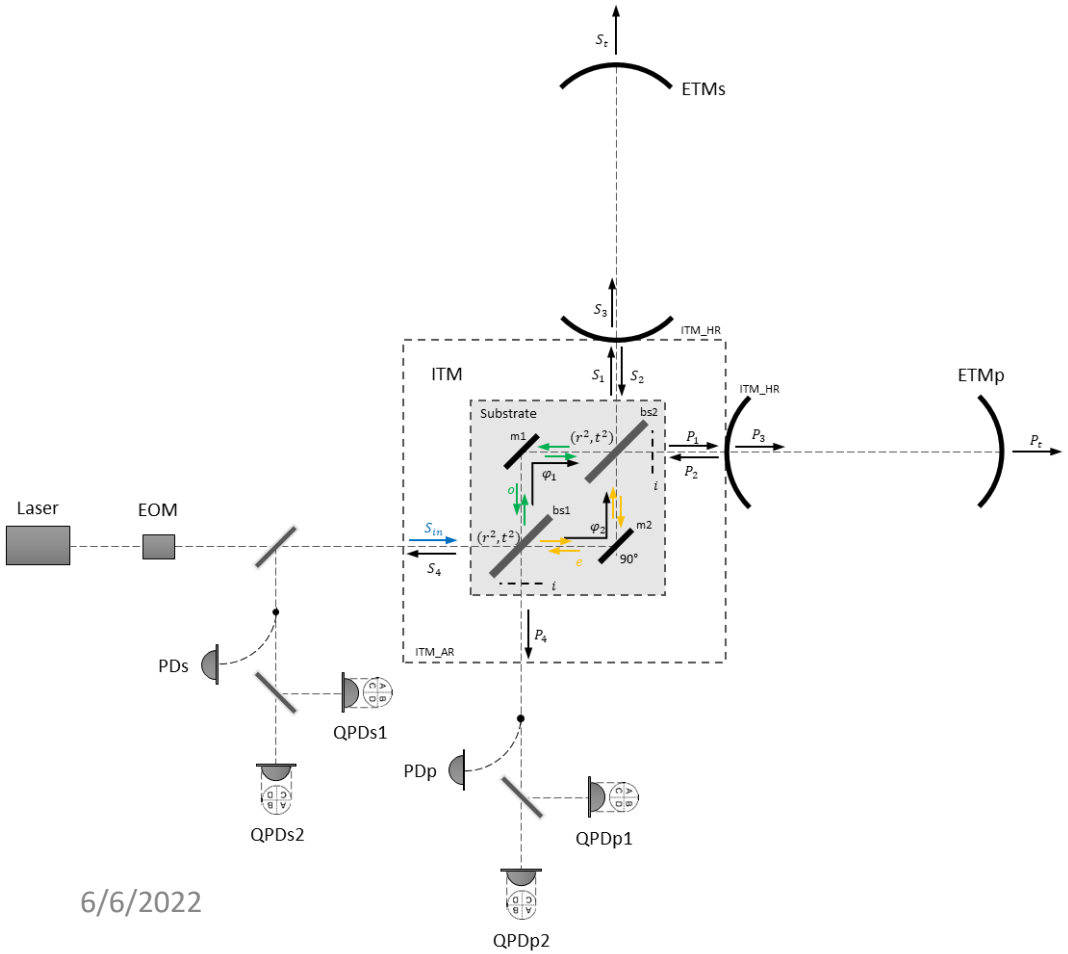


5°

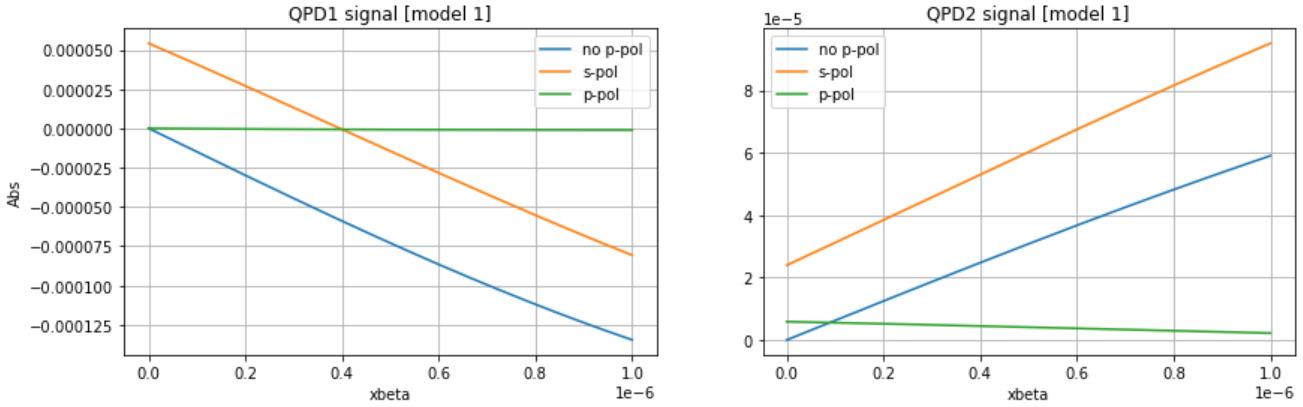


Preliminary ASC simulations (single arm)

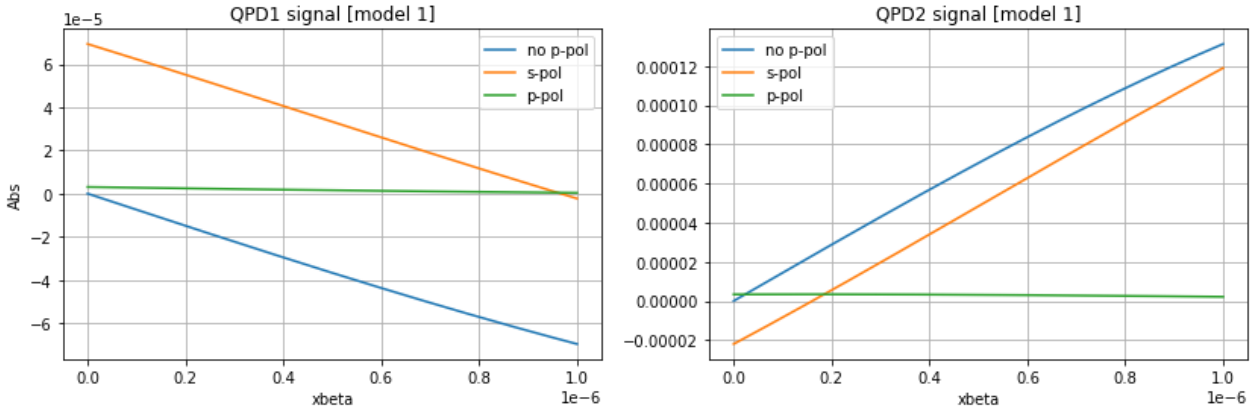
ROC and tilt x to create different modes	P-pol power Round-trip P4	P-pol mode content (one-way)		
		TEM00	TEM01	TEM02
Model 1	5%	10%	79.6%	10.4%



Gouy phase: QPD1: 40°, QPD2: 130°

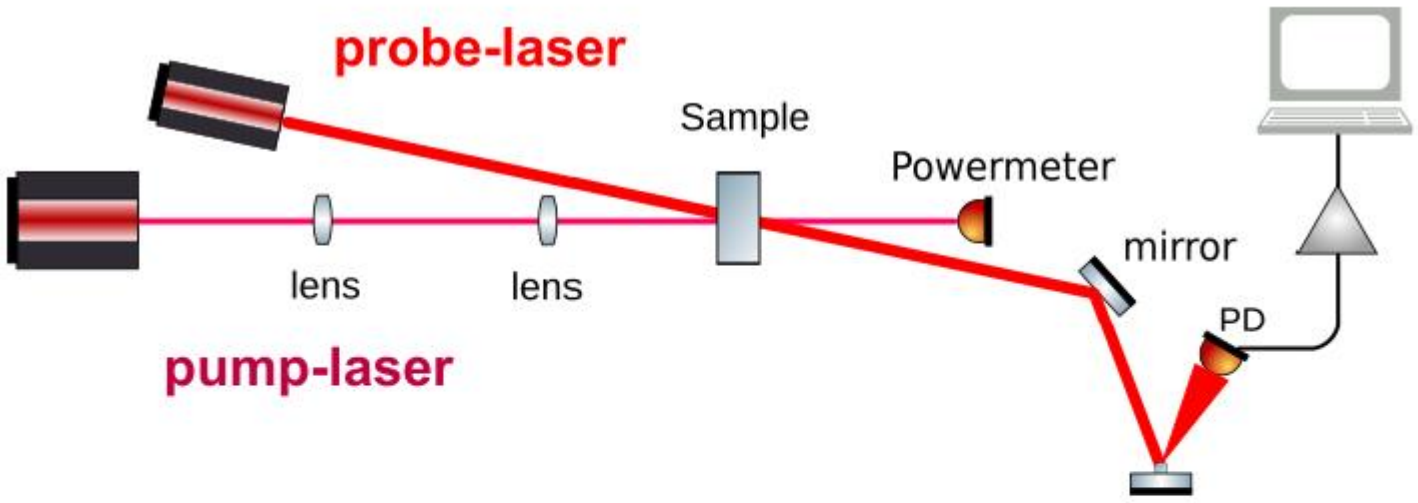


Gouy phase: QPD1: 0°, QPD2: 90°



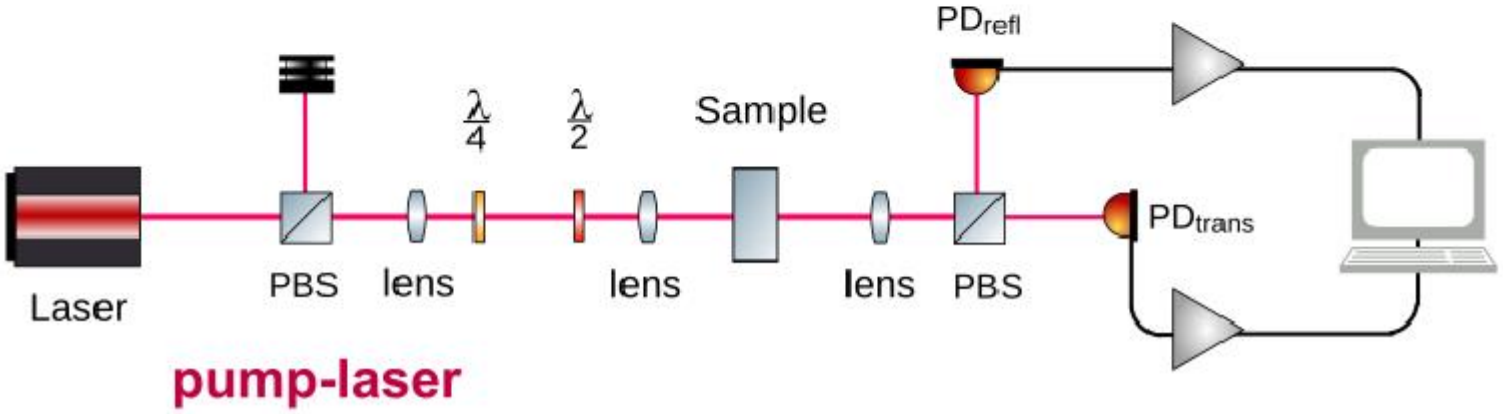
Characterization setup at NAOJ

Absorption:
photothermal common-path interferometer



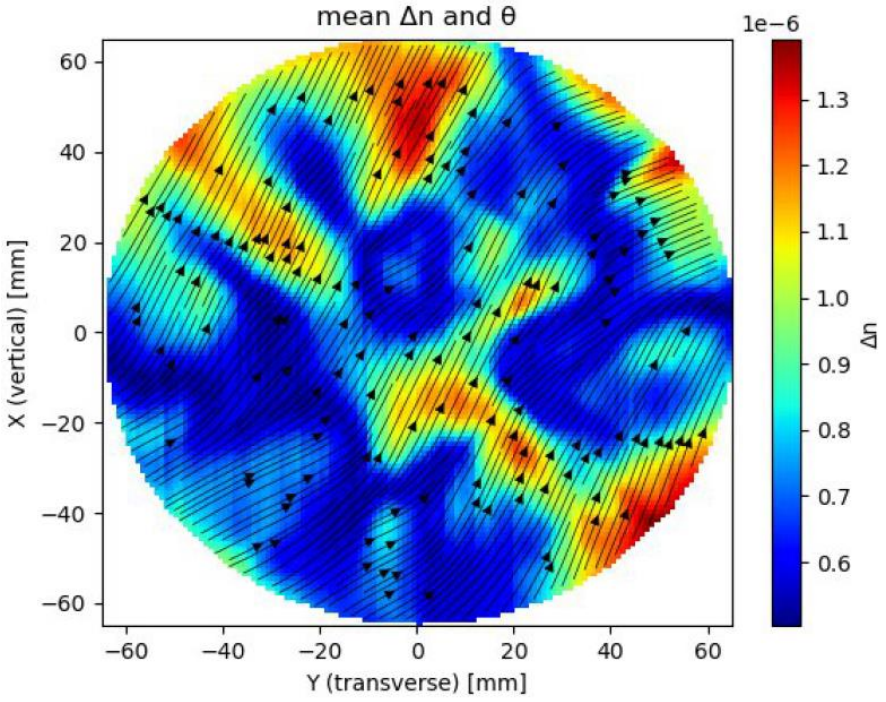
Birefringence:

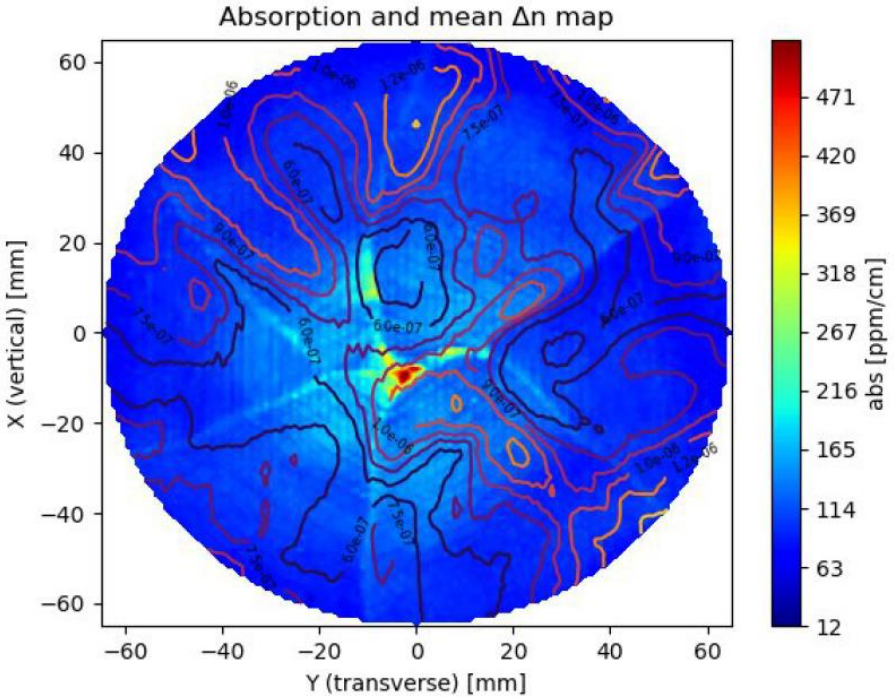
Single-pass polarization rotation



From birefringence to Δn

Δn_{RMS} is within original specs

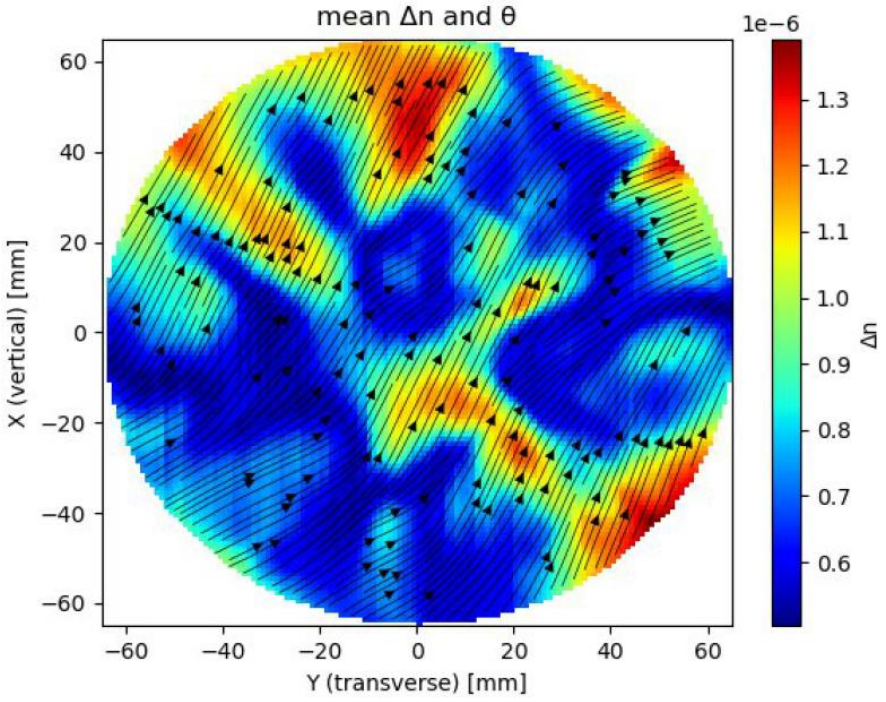


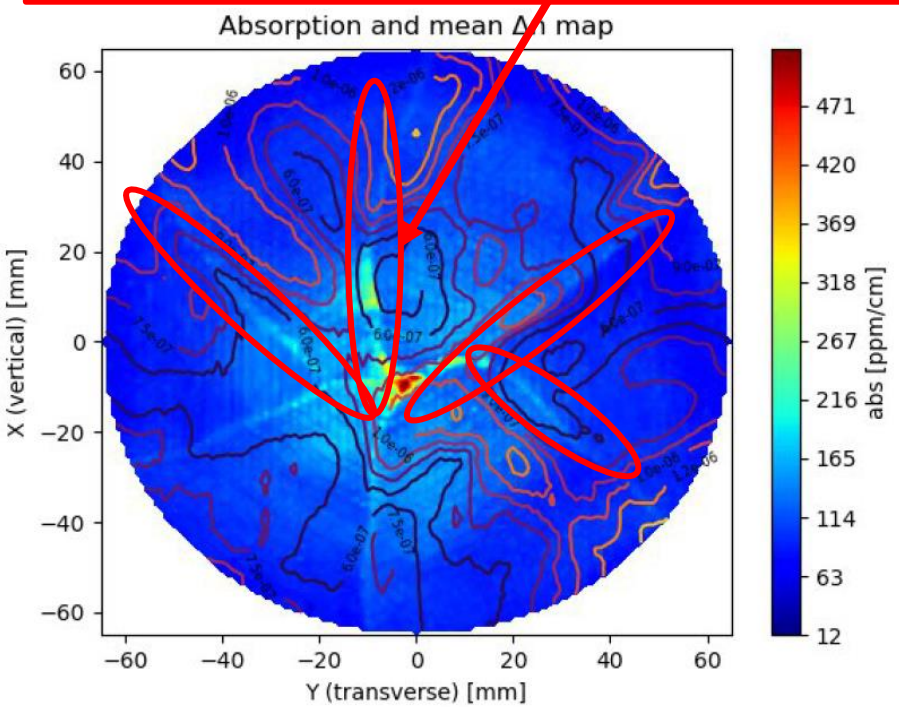


From birefringence to Δn

Δn_{RMS} is within original specs

Correlation between absorption and internal stress leading to birefringence

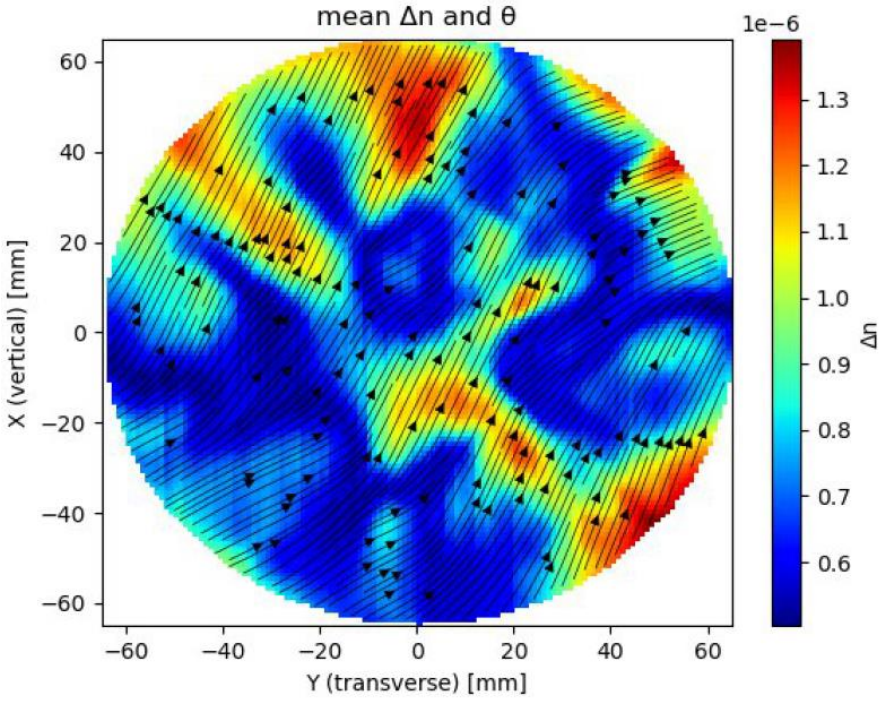


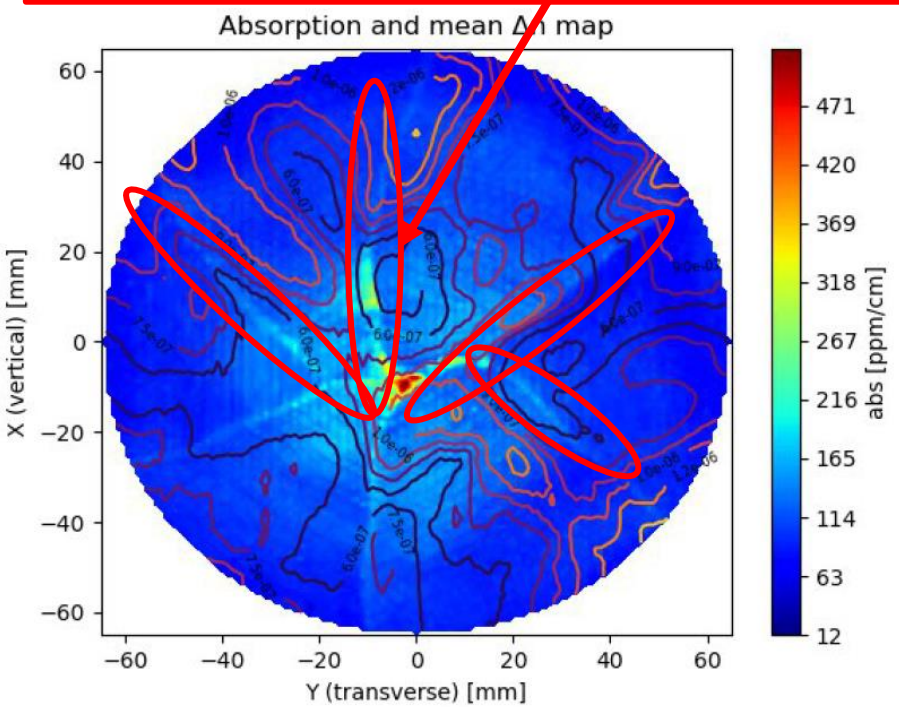


From birefringence to Δn

Δn_{RMS} is within original specs

Correlation between absorption and internal stress leading to birefringence





Structural defects can be the cause of both absorption and birefringence*

*Paper submitted to Scientific Reports.

Closing remarks

Sapphire substrates are challenging:

1. Absorption and absorption distribution depends on manufacturing technique
2. Birefringence homogeneity is an issue for IFO control
3. Interaction with crystal makers (companies) is necessary but slow due to the lack of interest from commercial environment

Main take-away messages:

1. Characterization of full-size substrates is necessary since many issues seems to be size dependent
2. Whichever crystalline material will be selected for 3G detectors, dedicated facilities for substrate productions need to be established to approach those issues in a “scientific way”.

Thank you!